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LITHIUM-THIONYL CHLORIDE BATTERY, (U)

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LITHIUM-THIONYL CHLORIDE BATTERY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) We have developed a satisfactory high rate D cell design which is suitable for use on both the BA5590 and GLLD load cycles. This cell has been further characterized by constant current discharge and voltage reversal at 0.3A, 1A and 3A at room temperature and -30°C. No dangerous behavior was observed during these tests or during short circuiting. We demonstrated the extremely high rate performance of the flat cylindrical cell.		

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The cell will deliver ~ 20 A.hr at 20A constant current and some 14 A.hr at 100A. We measured the short circuit and found it to be 1500A for the flat cylindrical cell. We also determined flat cell performance on GLLD test at 0°C and -30°C. We drove cells into voltage reversal at 3A after GLLD test, no dangerous behavior was noted.

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## I. Introduction

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The  $\text{Li}/\text{SOCl}_2$  inorganic electrolyte system (1-4) is the highest energy density system known to date. It consists of a Li anode, a carbon cathode and  $\text{SOCl}_2$ , which acts both as a solvent and cathode active material. The electrolyte salt that has been used most extensively is  $\text{LiAlCl}_4$ , but salts such as  $\text{Li}_2\text{B}_{10}\text{Cl}_{10}$  (5) and  $\text{Li}_2\text{O}(\text{AlCl}_3)_2$  (6) have also been used successfully in this system for improving the shelf life characteristics.

The main objective of this program is to develop high rate  $\text{Li}/\text{SOCl}_2$  cells and batteries for portable applications of the U. S. Army. The cells and batteries must deliver higher energy densities than are presently available and must be safe to handle under field conditions.

We carried out a detailed development (7) on the spirally wound D cell in order to establish their performance capabilities and to identify limitations in their performance and safety under various use and abuse conditions. Substantial progress was made in correction cell limitations. We found that spirally wound D cells approached the high rate requirements of the various U.S. Army applications more closely than do any other cell designs at the present time. We used this spirally wound D cell as a starting point and improved its rate capability to meet the requirements of two specific applications, namely the BA5590 battery for manpack radio and the battery for the GLLD Laser Designator.

We concentrated our effort on the development of the high rate spirally wound D cell during the first two quarters to determine whether it was possible for the D cell to meet the performance requirements of the GLLD Laser Designator. The results obtained in the second quarter showed that the high rate D cells could deliver 5.9 A.hr/cell compared to the 1 A.hr/cell realized from the presently used Ni/Cd batteries. An advantage of the D cell over other cell geometries and configurations so that the D cell can be produced at our lithium battery manufacturing plants with only slight modifications of the existing process which is used for manufacturing spirally wound  $\text{Li}/\text{SO}_2$  D cells. The results were encouraging and we are

continuing to improve the  $\text{Li}/\text{SOCl}_2$  D cell so that it can meet a variety of high rate requirements, including the GLLD application.

During the third quarter we concentrated our effort on the development of the three inch diameter flat cylindrical cell for the GLLD Laser Designator Battery. We initiated procurement of parts during the first quarter. The detailed design of the flat cell and its parts, as well as the design and fabrication of tooling needed to make the parts and cell was mostly completed during the third quarter. We have developed two types of flat cell, one is 0.45 inch thick while the other is 0.90 inch thick. The packaging efficiency of the battery with 0.90 inch cells is substantially higher than with 0.45 inch cells. Construction and performance characteristics of both types of flat cells were described in the report for the third quarter.

During the first two quarters we also examined the cell reaction mechanism using cyclic voltammetry. The information gained from this study indicated several approaches for improving both performance and safety of  $\text{Li}/\text{SOCl}_2$  cells. We evaluated the efficacy of these approaches during the third quarter and found that both performance and abuse resistance of the cells could be significantly improved by the use of additives. We evaluated some of the promising additives in the three inch diameter flat cell as well. During the fourth quarter we made additional engineering improvements to the 0.9 inch thick flat cell to enhance its performance. We found that the cell capacity and the abuse resistance of the D cell on the GLLD test were increased by the use of cathode additives. We also investigated the use of very long and thin electrodes to increase capacity on the GLLD test, with encouraging results.

During the fifth quarter we developed the D cell further with the aim of creating a cell design combining high capacity on the BA5590 test with the high rate performance necessary for GLLD test. This was done by increasing cathode capacity while maintaining a large electrode area. We also further defined the high rate performance of 0.9 inch flat cylindrical cell with impressive results.

## II. Laser Designator Battery/BA5590 Battery

A. The specifications of the GLLD Laser Designator Battery are as follows:

Dimensions	2.82" x 3.75" x 9.30"
Voltage 24V nominal	
	Maximum (OCV) 32V
	Average 24V
	End 20V

We considered the following types of individual cells for the above battery:

A. 16 spirally wound D cells; 8 in series, with the two series stacks in parallel.

B. 16 flat cells (3 inch O.D., 0.45 inch thick); 8 in series with the two series stacks in parallel.

C. 8 flat cells (3 inch O.D., 0.90 inch thick) in series.

D. 8 cylindrical 1.8" diameter spirally wound cells in series.

The development of the D cells and the two types of flat cell were described in the four preceding reports (8-11). The original GLLD duty cycle was: 17.5A for 0.0355 sec followed by 1.8A for 0.0145 sec; this cycle continues for 3 minutes. This constitutes one burst. This three minute cycle occurs every thirty minutes. This duty cycle has been changed by the sponsor. The new duty cycle is: 20A for 0.029 sec followed by 3.2A for 0.021 sec; this cycle continues for 20 seconds every three minutes. These duty cycles are shown schematically in Fig. 1. Cell capacities on the new and old GLLD regimes are very similar, while the shorter duration of the burst gives less cell heating with the new regime.

B. The specifications of the BA5590 Manpack Radio Battery are as follows:

Dimensions:	4.4" x 2.45" x 5.00"
Voltage:	Nominal 12 or 24V
	Maximum (OCV) 15 or 30V
	Average 12.5 or 25V

End: 10 or 20V

Capacity at 70°F 10 A.hr (30 hr. rate)

Max. Rate: 2 hr rate

Duty for 30V operation: 8  $\Omega$  load for 0.100 sec followed by 39  $\Omega$  load for 1 min followed by 560  $\Omega$  load for 9 min.

The above is repeated.

The presently used batteries contain 10 Li/SO<sub>2</sub> D cells in series and parallel to meet the 15 and 30V requirements. In view of the higher OCV of the Li/SOCl<sub>2</sub> D cells (3.6V) only eight D cells are needed for the required voltage.

### III. Spirally Wound D Cell

#### Introduction

The use of spirally wound D cells is attractive for the GLLD Laser Designator Battery because the technology is well developed. The cell incorporates proven packaging with a hermetic glass-to-metal seal and a low pressure vent which is hermetic until opening on short circuiting or other abusive use. The spirally wound cell is also easy to construct and is thus a convenient vehicle to study the effect of cell construction variables on performance. Finally, the spirally wound  $\text{Li/SOCl}_2$  D cell can be manufactured at our lithium battery manufacturing facility with a minimum of alterations and new tooling.

We developed the  $\text{Li/SOCl}_2$  D cell for the BA5590 test during the first two quarters. Cells with improved current collection gave over 10 A.hr on test on the BA5590 test cycle. A test battery of 8 D cells was prepared which ran for over 100 hours on the BA5590 duty cycle.

We have developed the spirally wound D cell for the GLLD application by examining a number of different techniques for cathode current collection and adopting the most satisfactory ones. This gave a D cell which, tested in pairs, gave 5.9 A.hr/cell on the GLLD test cycle. We examined a number of cathode additives in the spirally wound D cell which increased cell capacity to 7.3 A.hr with improved abuse resistance during voltage reversal. We then explored the limits of high rate performance for conventional  $\text{Li/SOCl}_2$  D cells by use of cathode pretreatment and extremely long electrodes to give a D cell providing 8.05-8.4 A.hr on the GLLD test. During the fifth quarter we returned to the BA5590 test and developed the spirally wound D cell for satisfactory performance on both BA5590 and GLLD applications.

#### Experimental

The improved electrode configurations for the optimized high rate D cell were evaluated in D cells of standard hermetic construction. These cells incorporate a hermetic G/M seal feedthrough and G/M seal low pressure vent

which is hermetic until opened on short circuit or other abusive treatment. The electrode stack, consisting of catalytic carbon cathode, lithium foil anode and glass fiber separator paper is wound about a mandrel and inserted into the can. The anode tab is welded to the centerpost in the G/M feedthrough while the cathode tabs are welded to the can during welding of cell top to can. The cells are filled using a special piece of apparatus which allows us to evacuate the welded cell through the fill port and then add electrolyte to the evacuated cell. The fill tube is then closed, first by crimping, then by resistance welding to create a hermetic cell.

We evaluated the D cells on the specified BA5590 and GLLD test loads using a mechanical timer and relay for the BA5590 test and a specially built micro-processor controlled pulse discharger for the GLLD test. We also discharged cells at three current levels: 0.3A, 1A and 3A using conventional DC power supplies and load resistors to assure constant current behavior throughout the test. Cell discharges at  $-30^{\circ}\text{C}$  were done in a Blue-M Versa-Range test chamber after the cells were allowed to equilibrate at  $-30^{\circ}\text{C}$ , usually overnight. Cell wall temperatures were measured by attaching a type J thermocouple to the side of the cell with tape and conductive paste. Data were recorded on a variety of conventional stripchart recorders as well as Linsels LD-12 12-channel recorder and Gould high speed recorders.

### Results and Discussion

While D cells tested early in the program gave satisfactory performance of over 10 A.hr on the BA5590 test, they had a lower capacity on the GLLD test. The later designs with very long cathodes gave better performance on GLLD, but the BA5590 performance was reduced. We developed a new D cell design using the cathode pretreatment process with a 28" cathode. This length was selected to allow a substantial excess of lithium capacity for improved abuse resistance during voltage reversal. The performance of two typical cells of this new design are shown in Figures 2 and 3. The cell life on test is superior to that of the earlier cell type (Fig. 4) by some 25-30% while the load voltage on the 1  $\Omega$  load was also increased from near 2.8 to above 3.0V for most of the cells life.

With this improvement in BA5590 and GLLD performance in hand (compared to the situation at the beginning of the project) we evaluated these cells for constant current performance at moderate rates, as a quick check of cell capacity and quality. Two cells were discharged at 1A, as shown in Figures 5 and 6. The cell capacity of 11.5 A.hr was somewhat less than expected in comparison with a cell with 20" electrodes as shown in Fig. 7. The cathode pretreatment process was suspected as the cause of the problem, which was confirmed when a cell with 20" pretreated cathode gave only 8.6A hr at 1A as shown in Figure 8.

While the 1A capacity of 11A.hr was still reasonably good, we decided to modify the cathode pretreatment process, reducing the cathode length to 26", giving a cell which will give good performance on BA5590, GLLD and constant current discharges. On the BA5590 test this type of D cell ran for 103 hours as shown in Figure 9, giving a capacity of some 11 A.hr. The same cell type was tested on the GLLD test, where it delivered over 220 bursts, or 7.7 A.hr/cell as shown in Figure 10.

This cell design was selected for the D cells for delivery to the sponsor at the end of the present contract. Accordingly, we characterized the performance and the abuse resistance of this cell in some detail. The results are presented below.

The polarization characteristics of this cell at 25°C are shown in Fig. 11. Note that the cell voltage remains above 3.0 volt up to a discharge current of 7.0A. The cells were discharged at currents of 0.3, 1.0, 3.0 and 10A at 25°C. Both the cell voltage and the wall temperature were monitored during the test. The results are shown in Fig. 12 through 15. At 0.3A the cell delivered approximately 10.8 A.hr (Fig. 12) to 3.0 volt cutoff. The operating cell voltage was 3.5 volt during most of the discharge. The cell wall temperature remained below 24°C during the entire discharge. At 1.0A, the cell delivered 9.4 A.hr (Fig. 13), the cell operating voltage remained above 3.25 volt during most of the discharge. The thermocouple malfunctioned during this test and that is why there was no temperature recording during the test. At 3.0A, (Fig. 14)

the cell delivered approximately 9.2 A.hr. The cell operating voltage was 3.2 volt during most of the discharge. The cell wall temperature increased during the test up to 37°C. At 10A (Fig. 15) the cell ran for 28 minutes, delivering a capacity of approximately 4.8 A.hr prior to the mild venting. The cell operating voltage was approximately 2.7 volt, while cell wall temperature increased substantially during the test, reaching 95°C towards the end of the test. The cell did not exhibit any unsafe behavior during the test. Li/SOCl<sub>2</sub> D cells of earlier designs (12) exploded on 10A test.

We determined the abuse resistance of the above cells by driving them into reversal at 25°C at constant currents of 0.3, 1.0 and 3.0A. We monitored both the cell voltage and the wall temperature of the cells during this abuse test. Voltage and the temperature profiles of the D cell on 0.3A reversal at 25°C is shown in Fig. 16. The cell voltage stabilized at near zero volt after the initial drop on 0.3A reversal, and remained at near zero volt all throughout the 35 hr duration of the reversal. The cell wall temperature increased only slightly at the beginning of the reversal but remained below 30°C. There was no cell venting or explosion, in contrast to the D cells of earlier designs (13). The above cell was discharged to 10.8 A.hr before being reversed for 10.5 A.hr worth of capacity, to a total capacity of 21.3 A.hr which was well over the stoichiometric lithium capacity of 18 A.hr.

The voltage and the temperature profile of another cell of similar construction but having a cathode additive 2 on 1.0A reversal at 25°C is shown in Fig. 17. Note that the cell wall temperature increased initially to 45°C but then declined to 25°C and remained there for the duration of the reversal. The cell voltage remained locked at virtually zero volt all throughout the reversal lasting for 18 hrs. This is a typical demonstration of the "voltage clamp" mechanism that makes these cells safe on reversal. There was no cell venting or explosion.

The voltage and the wall temperature profile of another D cell on 3.0A reversal at 25°C are shown in Fig. 18. The cell temperature increased sharply at the start of the reversal to approximately 100°C and then declined to 28°C on continued reversal. The cell voltage clamped at -0.3 volt during the reversal which was continued for 3.3 hours. The cell exhibited only mild venting.



There was no cell bulging or explosion. The operation of the "voltage clamp" to achieve safety on reversal was further demonstrated by this experiment.

The performance and the abuse resistance of the standard high rate D cell is now reasonably well defined at room temperature. We then examined the performance of these cells at  $-30^{\circ}\text{C}$  to determine the performance penalty associated with low temperature discharge.

A polarization curve for a standard D cell at  $-30^{\circ}\text{C}$  is shown in Figure 19. The drop in voltage at a given load relative to room temperature is pronounced, even at low current drains. A standard D cell was discharged at  $-30^{\circ}\text{C}$  on 0.3A load. The cells delivered 7A.hr to a 2V cutoff with only a very moderate rise in temperature as shown in Figure 20. This represents approximately 65% of the capacity obtained at room temperature. A standard D cell with cathode additive 2 was discharged at 1A at  $-30^{\circ}\text{C}$ . This cell gave 5.15 A.hr as shown in Figure 21 with a greater increase in cell temperature. This corresponds to 55% of the capacity delivered at room temperature. As a final high rate test at  $-30^{\circ}\text{C}$ , we discharged a standard D cell at  $-30^{\circ}\text{C}$  on 3A load shown in Figure 22. The temperature rise during discharge was somewhat greater than noted at the low currents while the capacity of 4.8 A.hr was quite comparable to the 1A capacity and 52% of the room temperature capacity. Besides the capacity loss at  $-30^{\circ}\text{C}$ , there is a power loss as well due to the lower voltage plateaus as shown in Table 1.

These cells discharged at  $-30^{\circ}\text{C}$  were also driven in voltage reversal at constant currents of 0.3 and 3A. There was no venting or other misbehavior after 23 hours of reversal at 0.3A at  $-30^{\circ}\text{C}$ . Again, the cell voltage remained at zero volt showing the excellent voltage clamping characteristics. The standard D cell with cathode additive 2 was driven into reversal at 1A for 13 hours at  $-30^{\circ}\text{C}$  as shown in Figure 23. There is some cell heating as the cell enters reversal, but not enough to raise cell temperature above  $0^{\circ}\text{C}$ . There was no venting during this test. Again the cell voltage clamped at zero volt with concurrent lowering of cell temperature on prolonged reversal. The final voltage reversal test was of a standard D cell in 3A reversal at  $-30^{\circ}\text{C}$ . The temperature (measured at the cell wall) and voltage are shown in Figure 24.

There was a very large rise in temperature as the cell entered reversal, followed by a return of cell voltage to small positive voltages. This cell behavior may be due to thermal decomposition of the intermediate species we detected earlier in the program, giving a reversal of the cathode passivation. Thereafter the cell voltage declined and clamped at -0.3 volt as before without any cell explosion. There was evidence of mild cell venting.

Finally, we shorted a standard D cell with additive 2 in the cathode, through a shunt and monitored the cell voltage, the short circuit current and the wall temperature of the cell. The results are shown in Figure 25. Note that the cell delivered a short circuit current of 200A at a cell operating voltage of 1.0 volt. Both the current and the voltage remained at a high level for 0.68 sec when the cell vented. There was no rupture of the cell. The cell wall temperature remained unchanged because the duration of the shorting was so brief.

#### Conclusion:

During the fifth quarter of this contract we have refined our several high rate D cell designs to produce a cell with good performance on both GLLD and BA5590 tests, while maintaining abuse resistant design features. We verified the good performance of this cell on both GLLD and BA5590 tests and selected this design as a new standard high rate D cell design with significant performance advantage over previous Li/SOCl<sub>2</sub> D cells.

We characterized this high rate D cell design by determining its capacity at currents ranging from 0.3A to 10A at room temperature at 0.3A to 3A at -30°C. We also carried out limited abuse testing on the standard high rate cell design by short circuiting and voltage reversal, both at room temperature and -30°C. The cells showed excellent abuse resistance on voltage reversal. There was no cell explosions on either shorting or reversal. The cells vented on a short circuit on prolonged reversal, the cell exhibited "voltage clamping" and the concurrent safe behavior.

#### IV. The Flat Cylindrical Cell

##### Introduction

We have developed the flat cylindrical cell, 3 inch in diameter and 0.9 inch thick, for the GLLD Laser Designator application. The details of the construction of the cell are described in the previous reports (9-11). The cell weighs approximately 225 gm. We optimized the internal electrode structures of this cell in order to obtain the best performance on GLLD load regime. The internal impedance of the cell was extremely low thus leading to a very low cell polarization and minimum cell heating on the GLLD load. The performance of the cell, as reported in the fourth quarterly report (11) was found to be outstanding. The cell delivered 300 pulses corresponding to a capacity of 21 A.hr at room temperature.

During the fifth quarter, we evaluated the performance characteristics of the above flat cell in the following area.

1. 0°C test on GLLD load.
2. -30°C test on GLLD load.
3. Constant current force discharge (reversal).
4. Short circuiting.
5. Continuous high current (20A, 100A) discharge.

The results are reported here.

##### Experimental:

The flat cylindrical cells were fabricated and assembled as described in earlier reports. These cells, as do the D cells, incorporate a hermetic G/M seal feedthrough and a G/M seal low pressure vent which is hermetic until opened. The cells are evacuated through the fill port and filled with electrolyte as are the D cells. The fill tube is then crimped and welded to produce a hermetic cell.

In general test procedures for the flat cell were identical to those for the

D cell, with some exceptions. Pressure measurements in flat cells were taken with a pressure transducer attached to the cell by a Swagelock fitting on a second fill tube specially incorporated into this cell. Because of the high short circuit current for the flat cylindrical cell, we designed and built a special fixture for short circuit testing. This fixture incorporates a 500 amp shunt for current measurement and is manually actuated through a 300 amp knife switch by a manual control rod extending through the wall of our abusive testing area. Electrical connection from the knife switch to the anode is made via a compression collet on the center post and a 1/16" x 4" x 8" copper strip forming a flexible connection. There is an electrically isolated voltage probe at the centerpost to allow voltage measurement unaffected by IR drop through the leads. Cathode connection to the cell is made via a 1/16" copper sheet bolted to the 500 amp shunt. This design features large areas for electrical contact and short electrical paths to keep external resistance to a minimum. From the current and cell voltage measured during shorting, we estimate the resistance of this fixture to be  $5 \times 10^{-4}$  ohm.

### Results and Discussion

1. 0°C Test on GLLD Load: One flat cell was soaked at 0°C for 6 hours prior to initiating the test on GLLD load profile (shown in Figure 1). Both the cell voltage and the wall temperature was monitored during the test. The results are shown in Fig. 26. The average cell voltage on 3.2A load was 3.2 volt while on the 20A load it was 2.75 volt. The cell delivered 11.4 A.hr to 2.5 volt and 14 A.hr to 2.0 volt. The cell wall temperature rose up to 10°C toward the end of the test. The cell delivered approximately 70% of its room temperature capacity of 20 A.hr at 0°C up to a 2.0 volt cutoff. This is quite satisfactory, considering the high rate pulsing requirements.

2. -30°C Test on GLLD Load: A flat cell was soaked at -30°C for three days and then it was tested on GLLD load profile shown in Fig. 1. The voltage profile of the cell on 3.2 and 20A pulse are shown in Fig. 27. The voltage regulation on 3.2A pulse was found to be significantly better than on 20A pulse. The cell delivered approximately 7.1 A.hr to 2.5 volt and 9.9 A.hr to 2.0 volt cutoff. This corresponds to a 50% reduction in cell performance up

to 2.0 volt cutoff. Again, considering the high rate requirements of the GLLD application, the performance at  $-30^{\circ}\text{C}$  was found to be quite satisfactory.

3. Constant Current Force Discharge: Several flat cells were force discharged at a constant current of 3A to voltage reversal for a period of from 20-30 hours after the regular discharge on the GLLD loads. None of the cells tested showed any undesirable behavior on this type of abuse. There was no cell venting or explosion. A typical voltage and temperature profile on reversal at 3.0A are shown in Fig. 28. Note that the cell temperature became constant after the initial rise to  $38^{\circ}\text{C}$ . The cell voltage clamped itself at zero volt within one hour of reversal and remained there for 20-30 hrs. Again, the voltage clamping mechanism was found to be operable in these flat cells thus making these safe on forced discharge.

4. Short Circuiting: We short circuited several flat cells using the short circuiting device described in the experimental section of this report. In one experiment we shorted the cell in short duration installments in order to measure the short circuit current without letting the cell to vent. The current and voltage profiles on the first shorting pulse are shown in Fig. 29. The cell delivered a short circuit current of 1,700A at a cell voltage of 0.8V. This corresponds to power output of 1.36 KW. The short circuit current remained virtually constant at around 1,500A for the duration of the short consisting of 0.12 second. The cell voltage remained constant at approximately 0.8 volt. It is interesting to note that the above short circuit characteristics of the cell represents a power density of approximately 2.7 KW/lb or  $0.21\text{ KW/in}^3$ . This is the highest power density capability of any primary or reserve cell known today. The temperature rise during this pulse was found to be rather modest. The cell is capable of delivering the above pulse power every half an hour without any cell heating or venting.

We repeated the shorting tests several times over several days, and we found that the cell consistently delivered short circuit currents in excess of 1500A at a cell voltage of 1.0 volt. The internal impedance of the cell turned out to be 1.7 milliohm, which is the lowest ever achieved in Lithium batteries to date. This is truly a super high rate cell.

On continuous shorting lasting for about a second, the cell vented. There was no rupture of the can, it only bulged. A photograph showing a fresh and a shorted cell is shown in Fig. 30. It appears that the high rate design of the cell also imparts additional safety in that the super high rate flat cells do not explode on either shorting or forced-discharge.

5. Continuous High Current Discharge: Flat cells were discharged at a constant current of 20A on a continuous basis, instead of pulse discharge as in GLLD application. The discharge curve is shown in Fig. 31. The cell operated at 3.2 volt and ran for 40 minutes above 3.0 volt corresponding to a capacity of 13A.hr. The cell showed a voltage recovery towards the end of the discharge. The total cell capacity realized above 2.0 volt was approximately 19.8 A.hr. On GLLD pulse mode we realized 20 A.hr, thus indicating that the cell performs equally well in pulse as well as in continuous mode.

We discharged a flat cell on a continuous current of 100A at 25°C. In this case we monitored the cell wall temperature, the cell internal pressure, along with the cell voltage. Since, the discharge was done through a variable resistor, the cell current was not controlled very precisely and therefore, we monitored the cell current as well. The results are shown in Fig. 32. The cell voltage was above 3.0 volt during most of its operation. The cell ran for 8.5 minutes to a voltage of 2.7 volt, corresponding to a capacity of 13.6 A.hr. The cell temperature increased steadily during the test and reached 80°C. The cell internal pressure began to increase after one minute into the test and reached 280 PSI after 6 minutes. The cell vented after 8.5 minutes. The high rate performance of the cell was found to be exceptional. The cell venting is intrinsically preventable by proper cell cooling.

#### Conclusion:

In summary, the super high rate performance of the cell on continuous load was found to be exceptional. The results are summarized as follows:

Current Drain	Operating Voltage	Power (W)	Power Density (W/in <sup>3</sup> )	Capacity (A. hr)	Total Energy (WHr)	Energy Density (WHr/in <sup>3</sup> )
20A	3.2	64	10	19.8	59	9
100A	3.0	300	47	13.6	41	6

The cell is capable of delivering significant amounts of energy at an 8 minute rate.

## V. Conclusion

The fifth quarter saw our areas of concentration divided as we optimized our high rate D cell for both GLLD and BA5590 applications while demonstrating increased capacity at high rates. A D cell design for delivery to ERADCOM has been selected and both the performance at the specified loads, and the abuse resistance of the cell was evaluated. No dangerous behavior was observed.

The high rate capability of the flat cell was verified during this quarter by discharge at 20A and 100A as well as by abusive short circuiting. During the final quarter we will more completely characterize the performance of this remarkable super high rate flat cell, as well as fabricate one hundred D cells for delivery.



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TABLE 1

Voltage Plateaus for Standard High Rate D Cells

Current (A)	Voltage at	
	-25° C	-30° C
0.3A	3.5V	3.1V
1.0A	3.30V	3.1V
3.0A	3.25V	2.9V
4.0A	3.2V	--
10.0A	2.7V	--

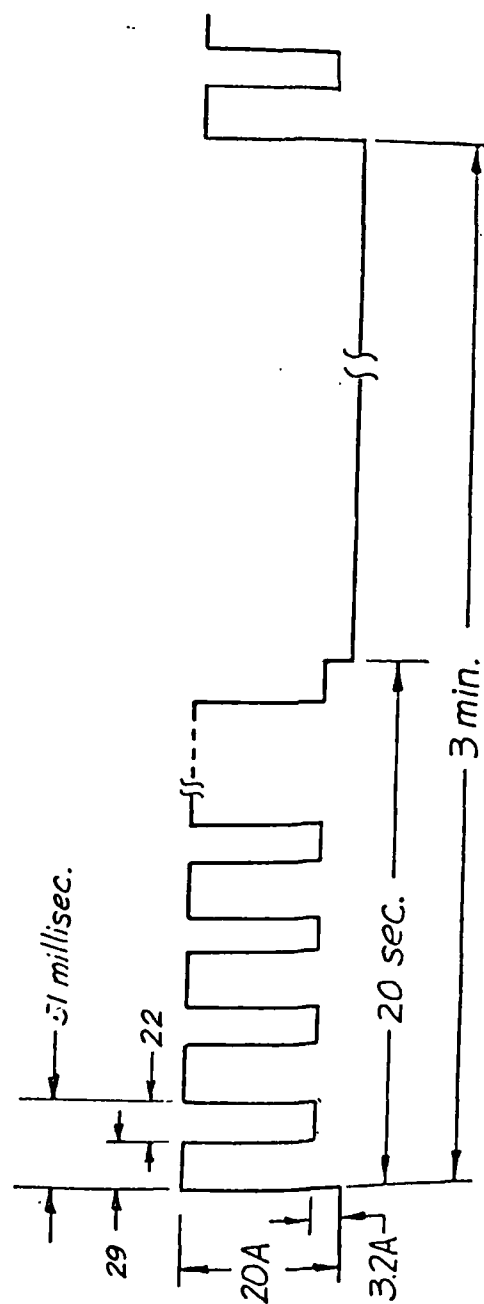


Fig. 1. Old and new duty cycles for the GLID battery for laser designator.

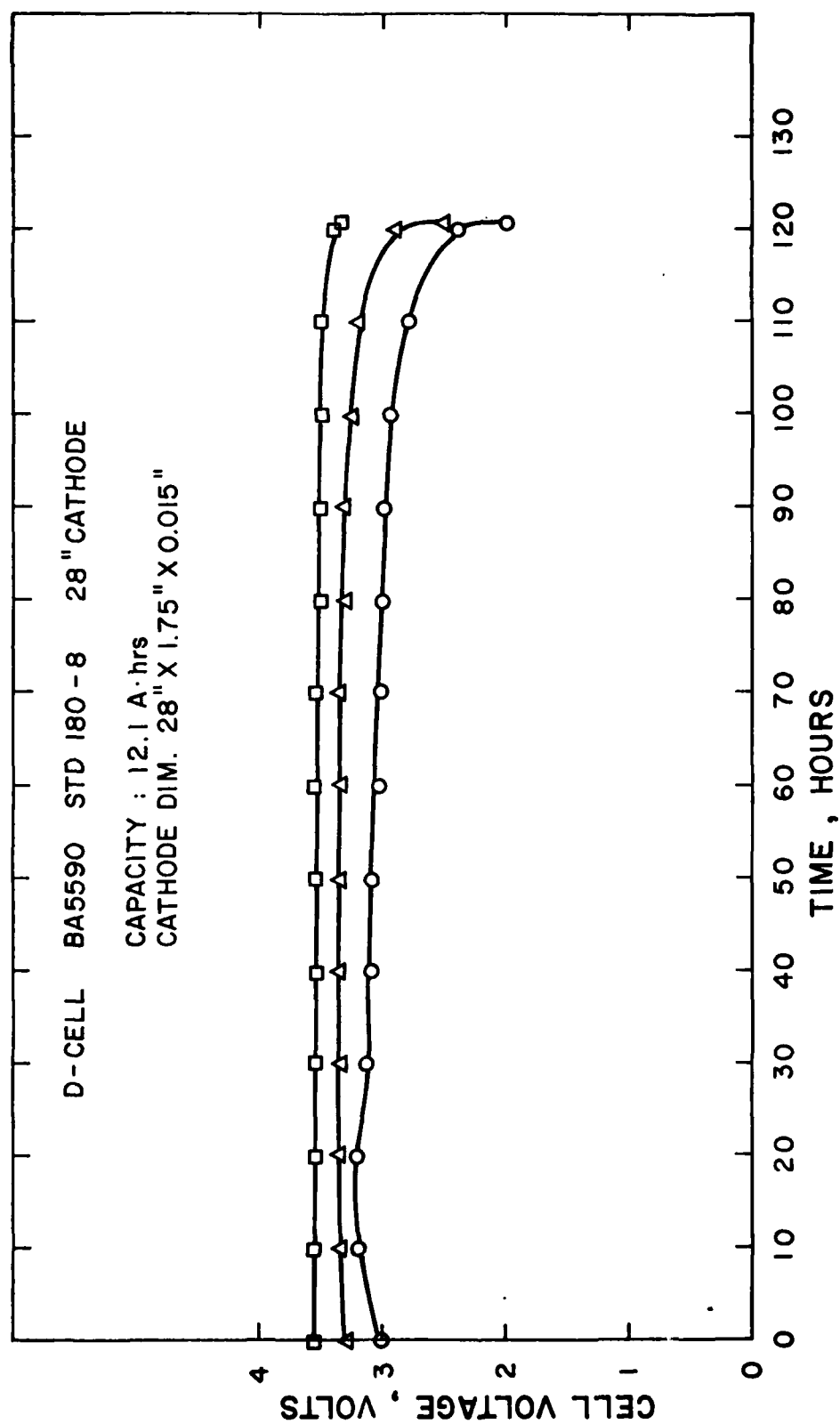


Fig. 2 Performance of a D cell with 28 inch cathode on the BA5590 test.

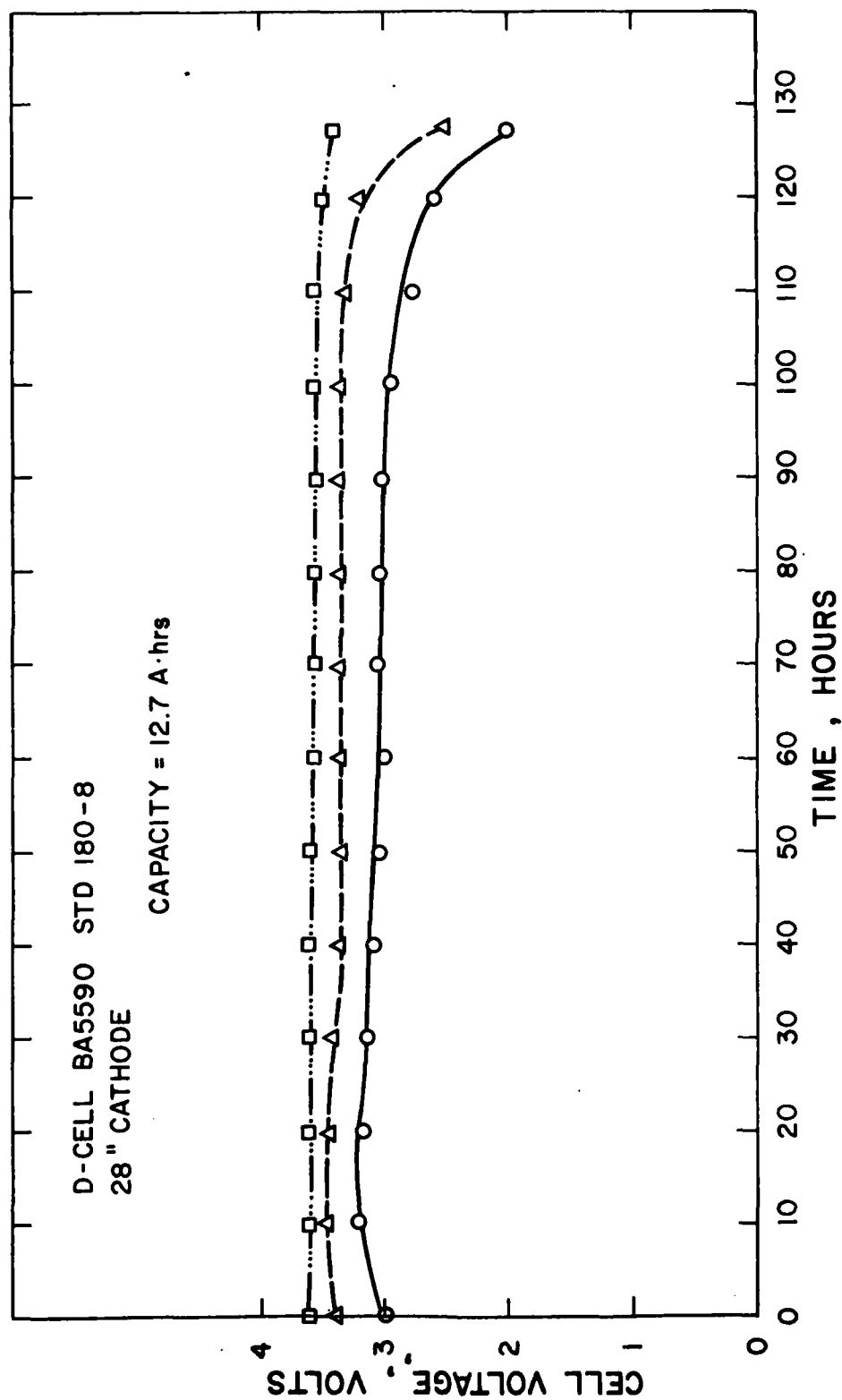


Fig. 3 Performance of a D cell with 28 inch cathode on the BA5590 test.

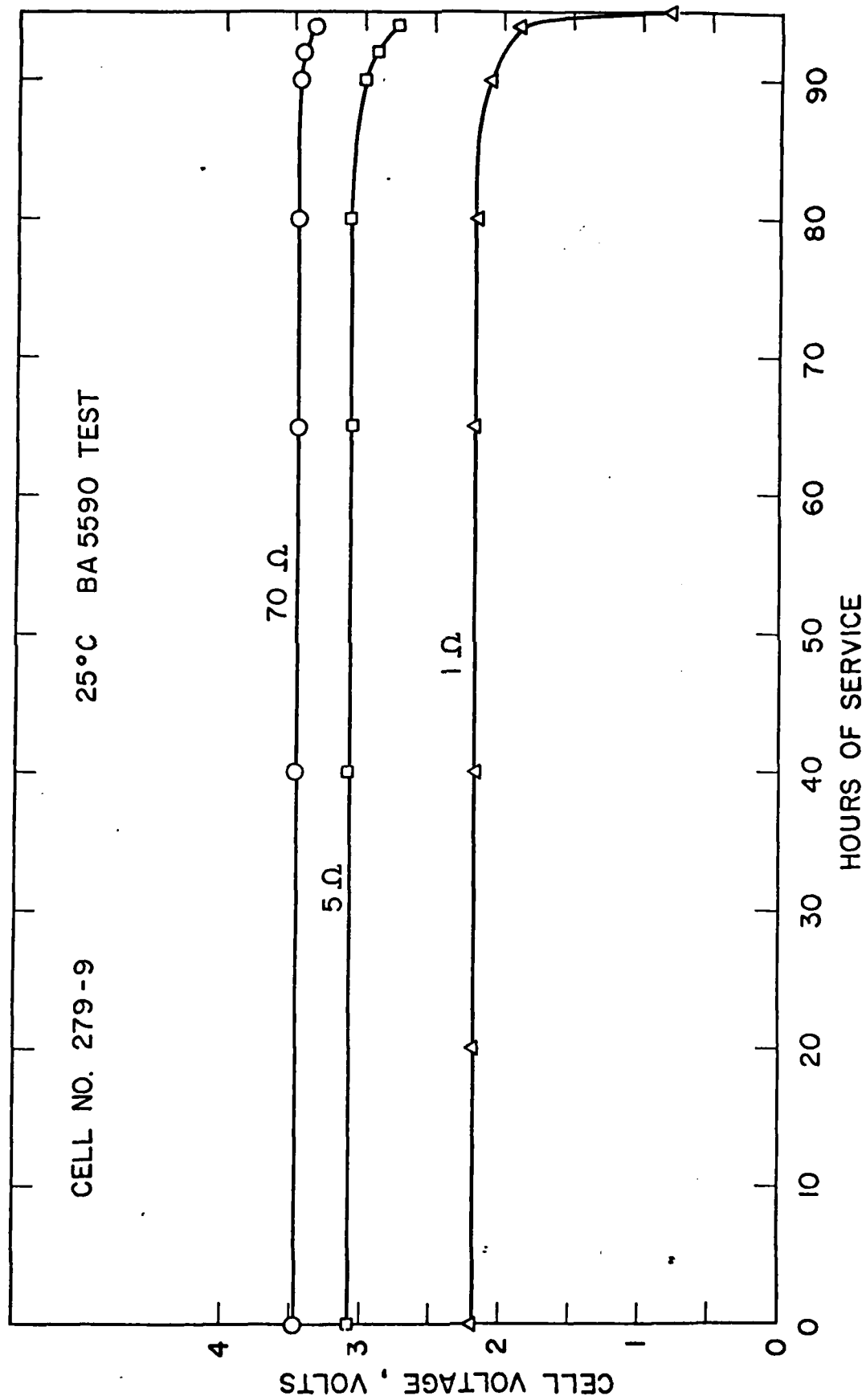


Fig. 4 Performance of an early high rate D cell on the BA5590 test.

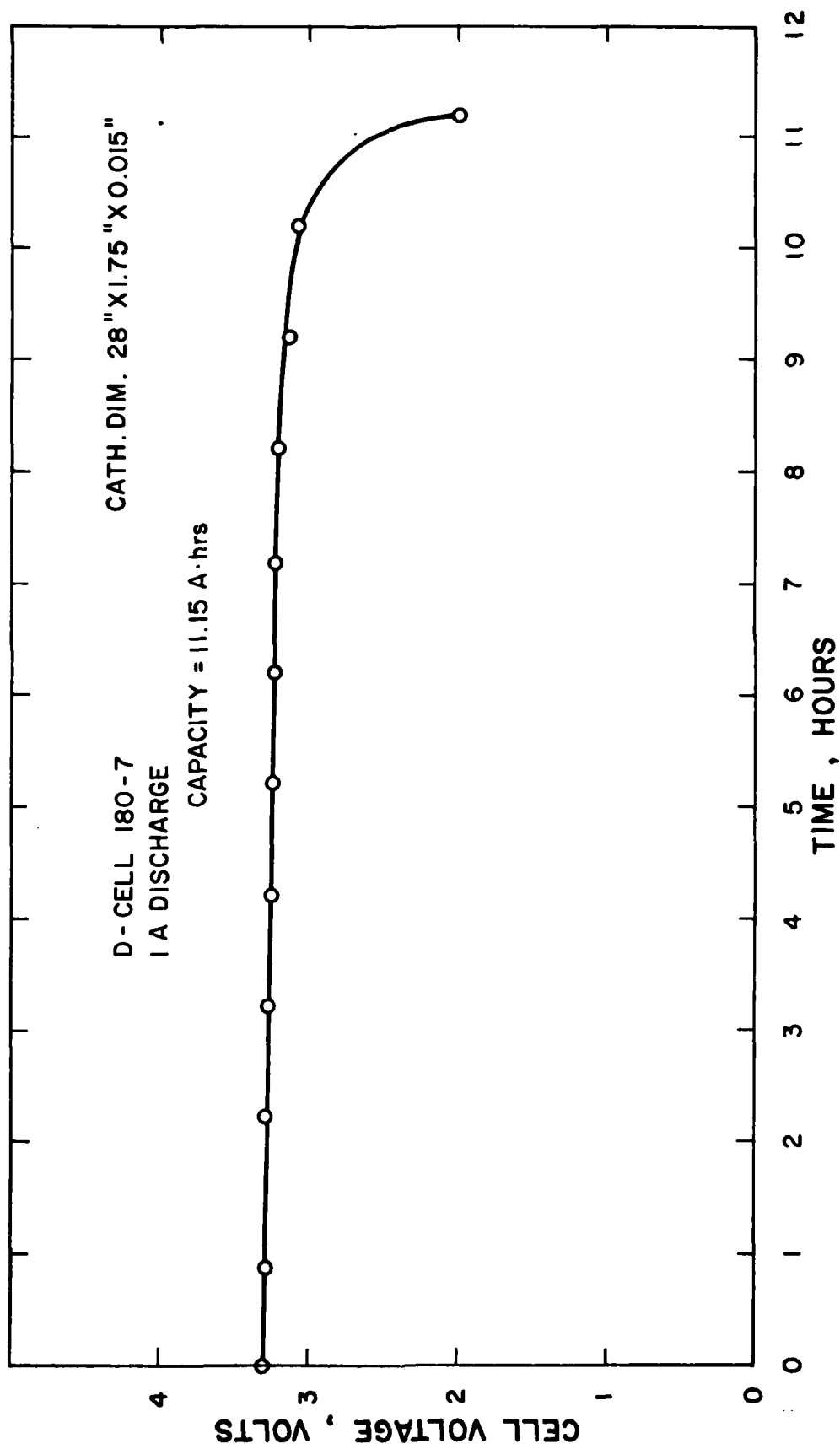


Fig. 5 Discharge of a D cell with 28 inch cathode at 1 amp at room temperature.



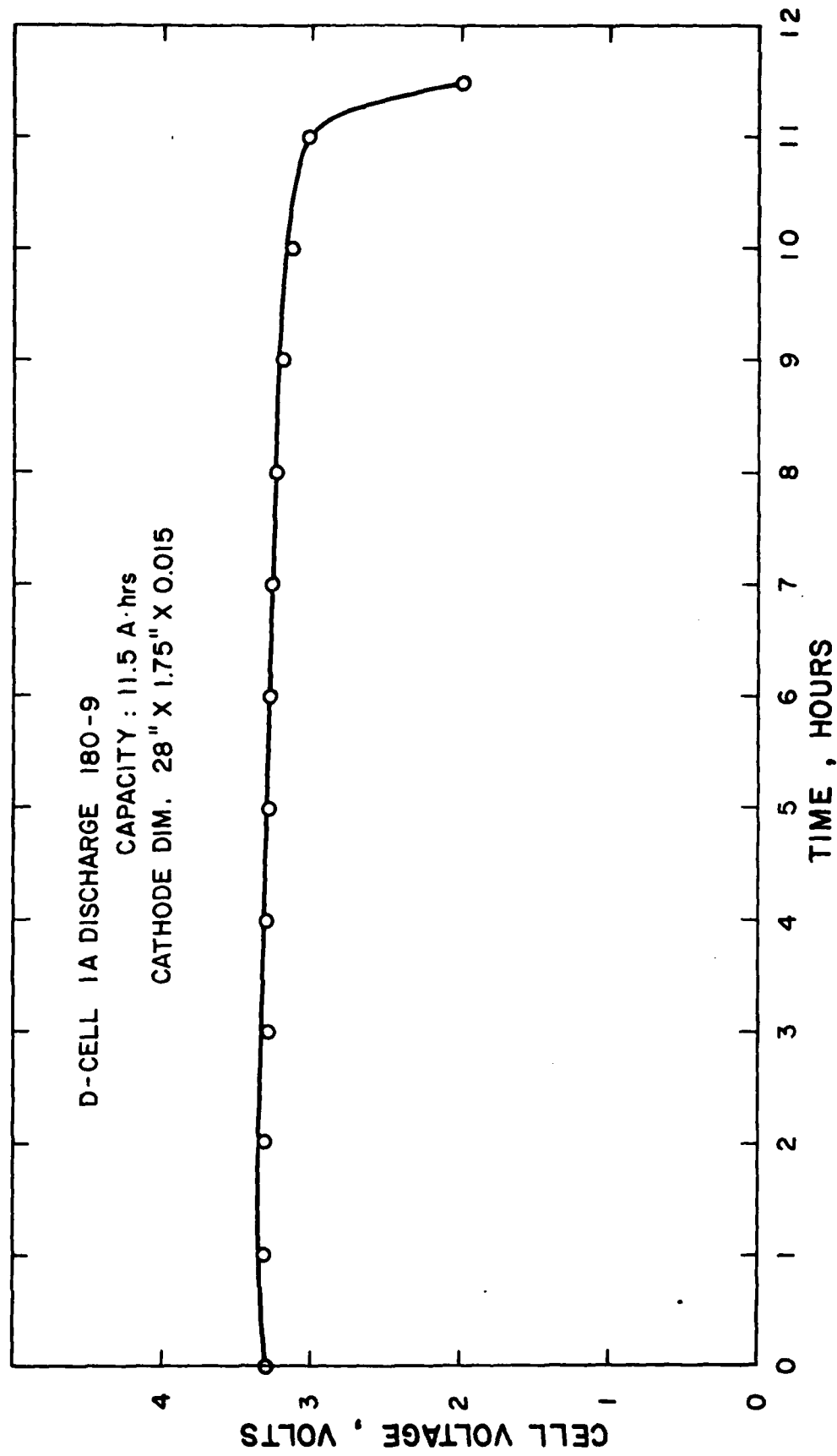


Fig. 6 Performance of a D cell with 28 inch cathode on 1 amp discharge at room temperature.

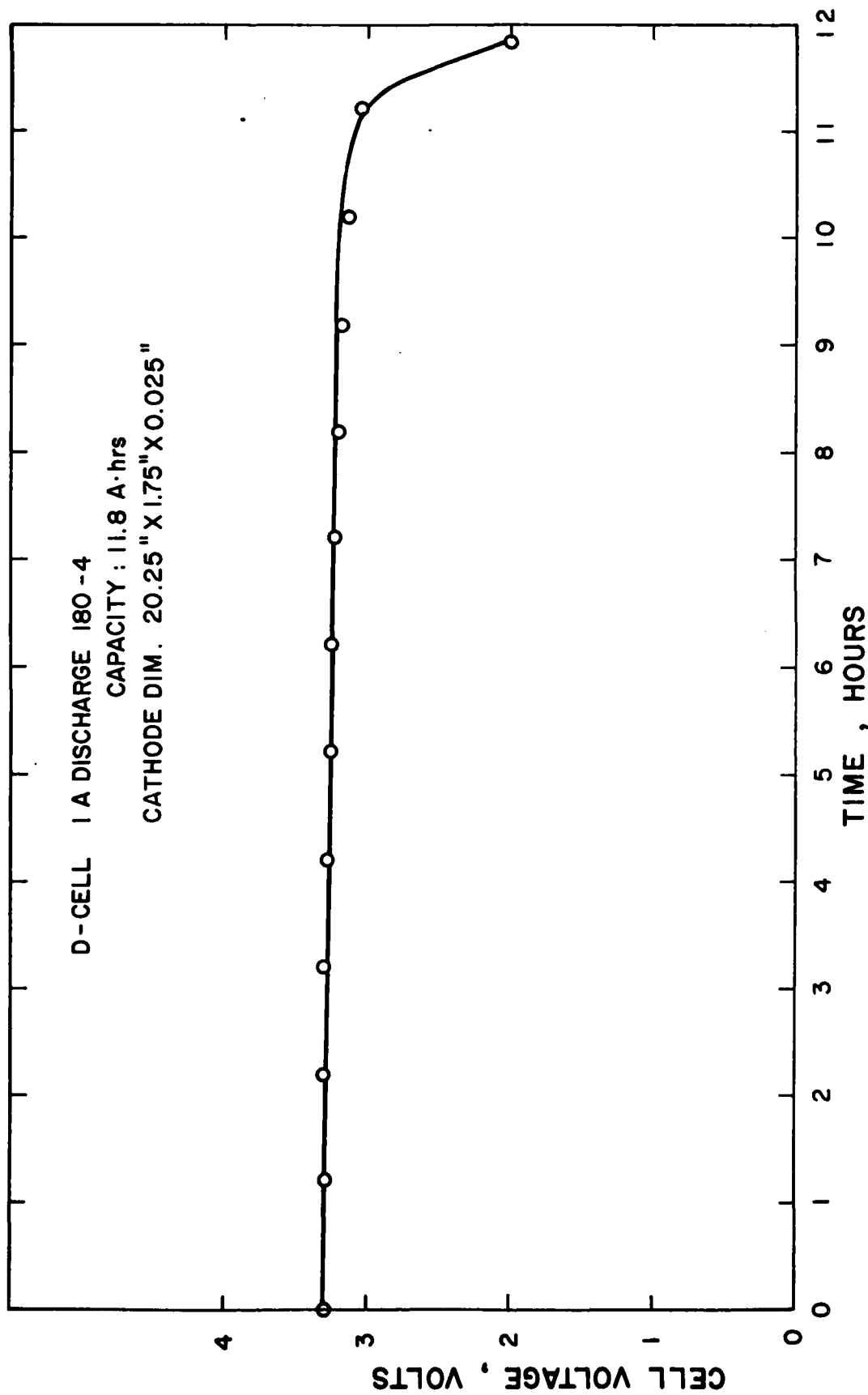


Fig. 7 Performance of a D cell with 20 inch cathode on 1 amp discharge.

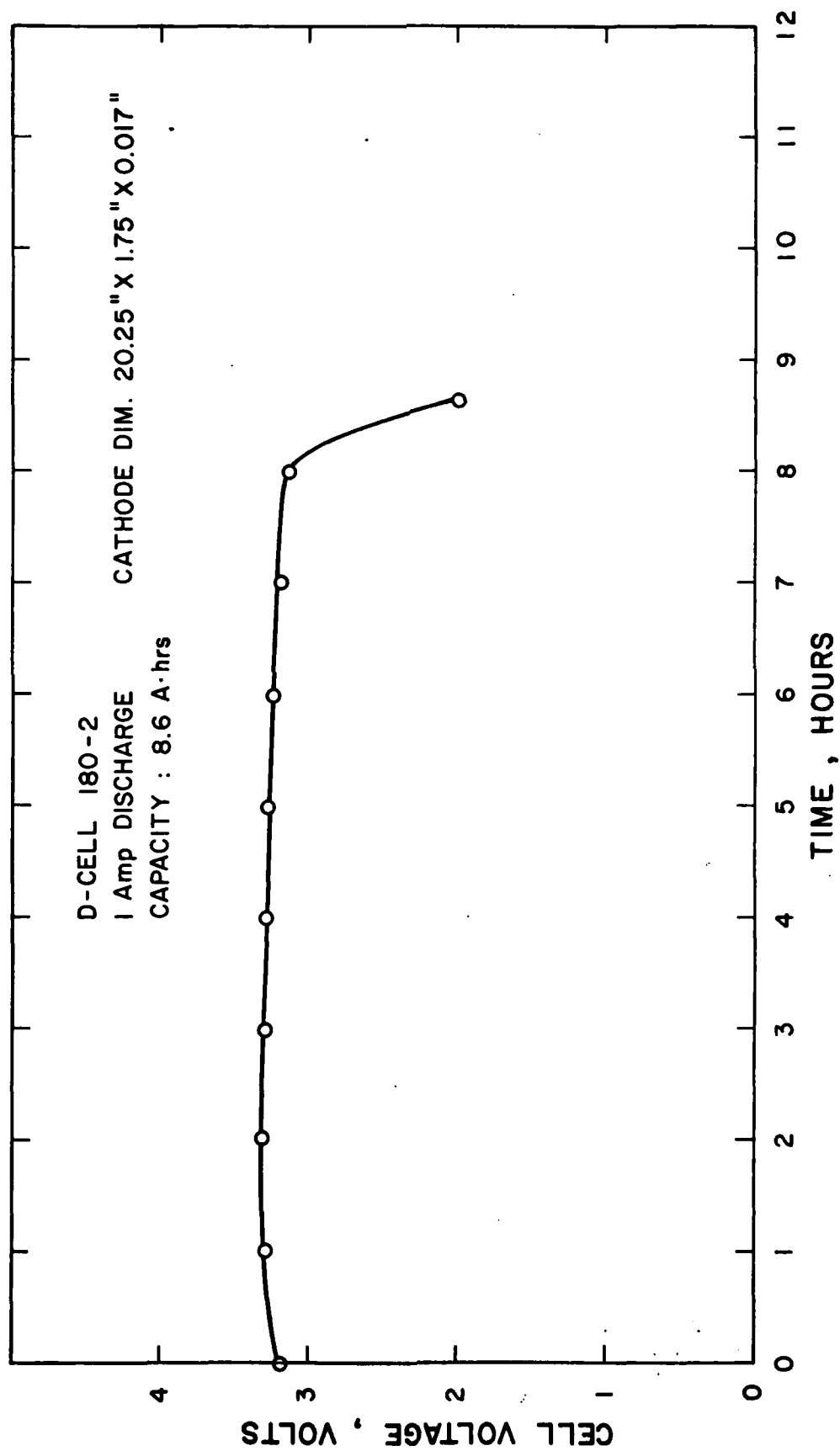


Fig. 8 Performance of a D cell with 20 inch pretreated cathode on 1 amp discharge.

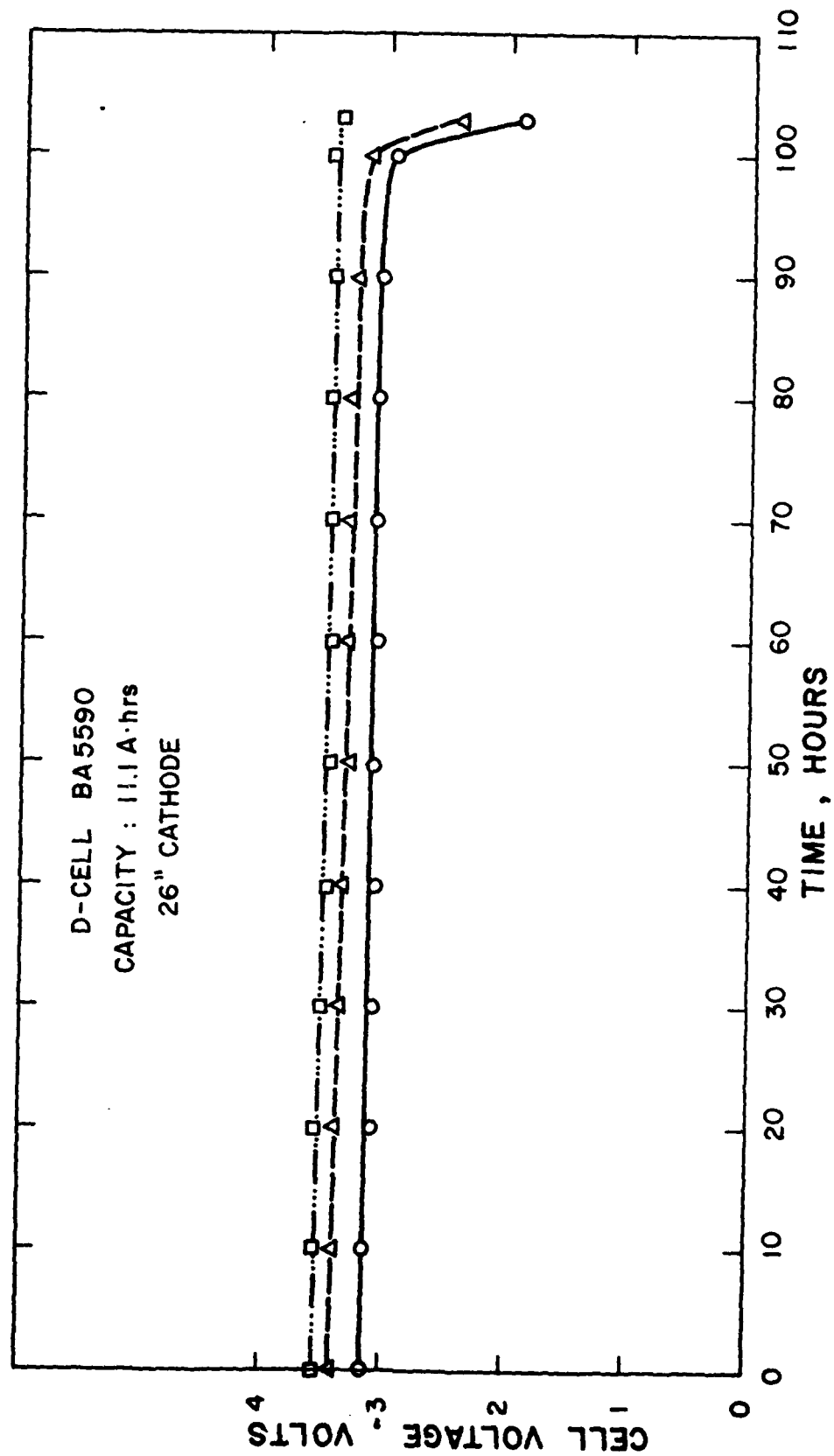


Fig. 9 Performance of D cell with 26 inch cathode on BA5590 test.

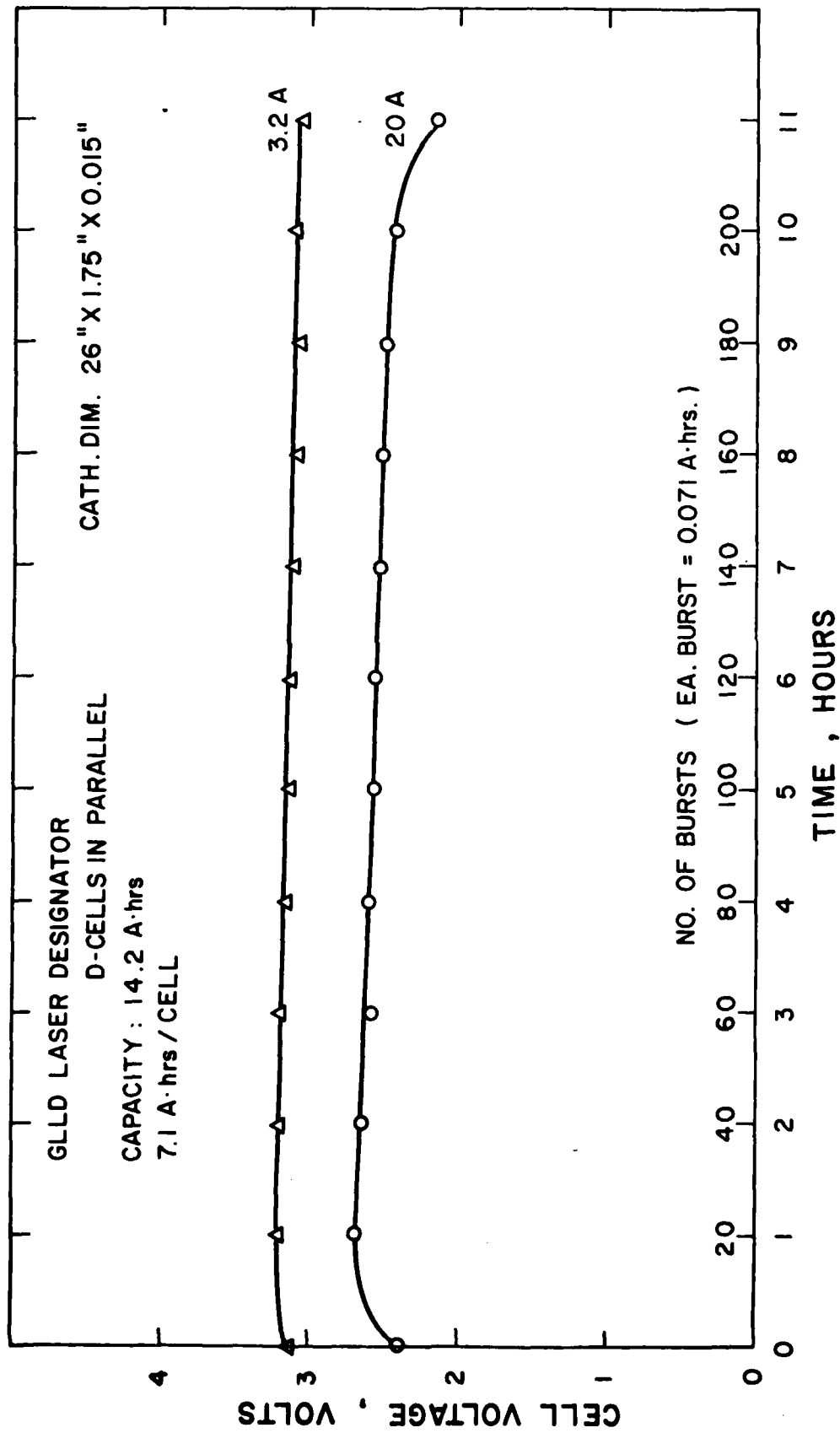


Fig. 10 Performance of a pair of D cells with 26 inch cathodes on GLLD test.

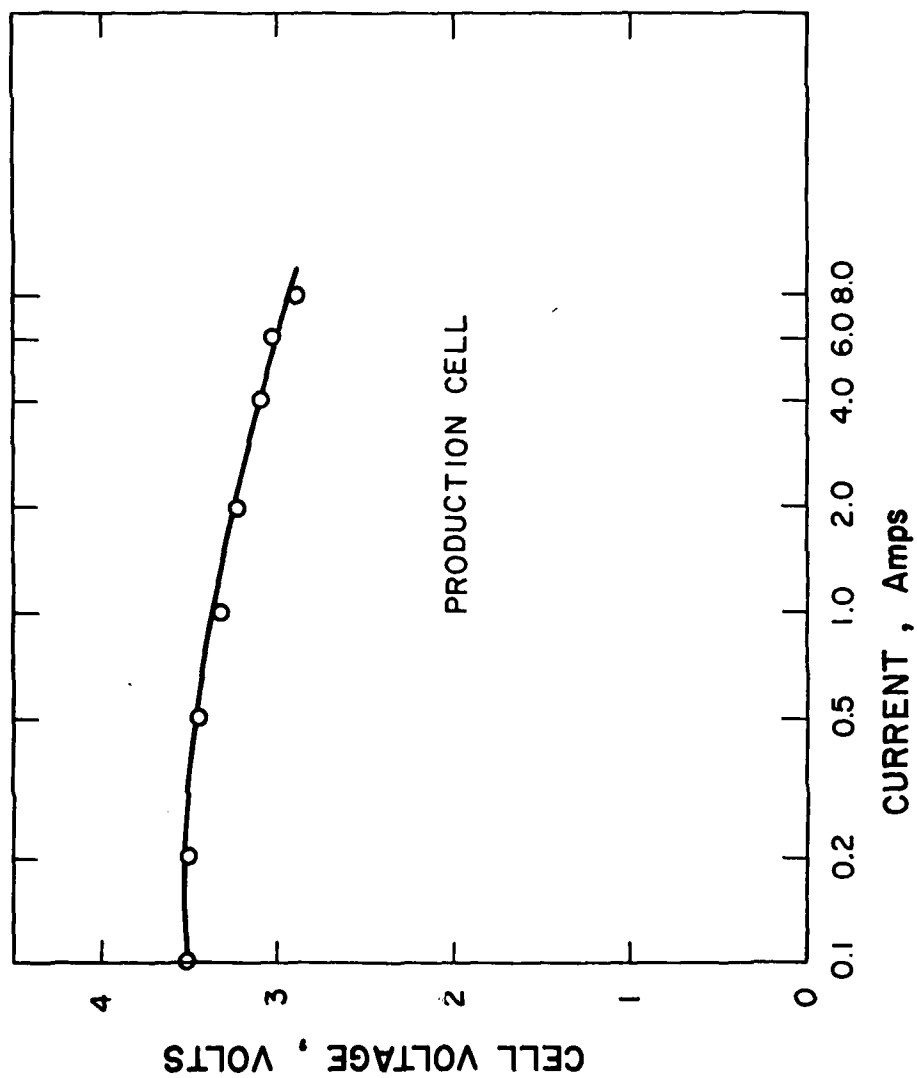


Fig. 11 Current vs. voltage plot for a 26 inch D cell from 0-8 amps.

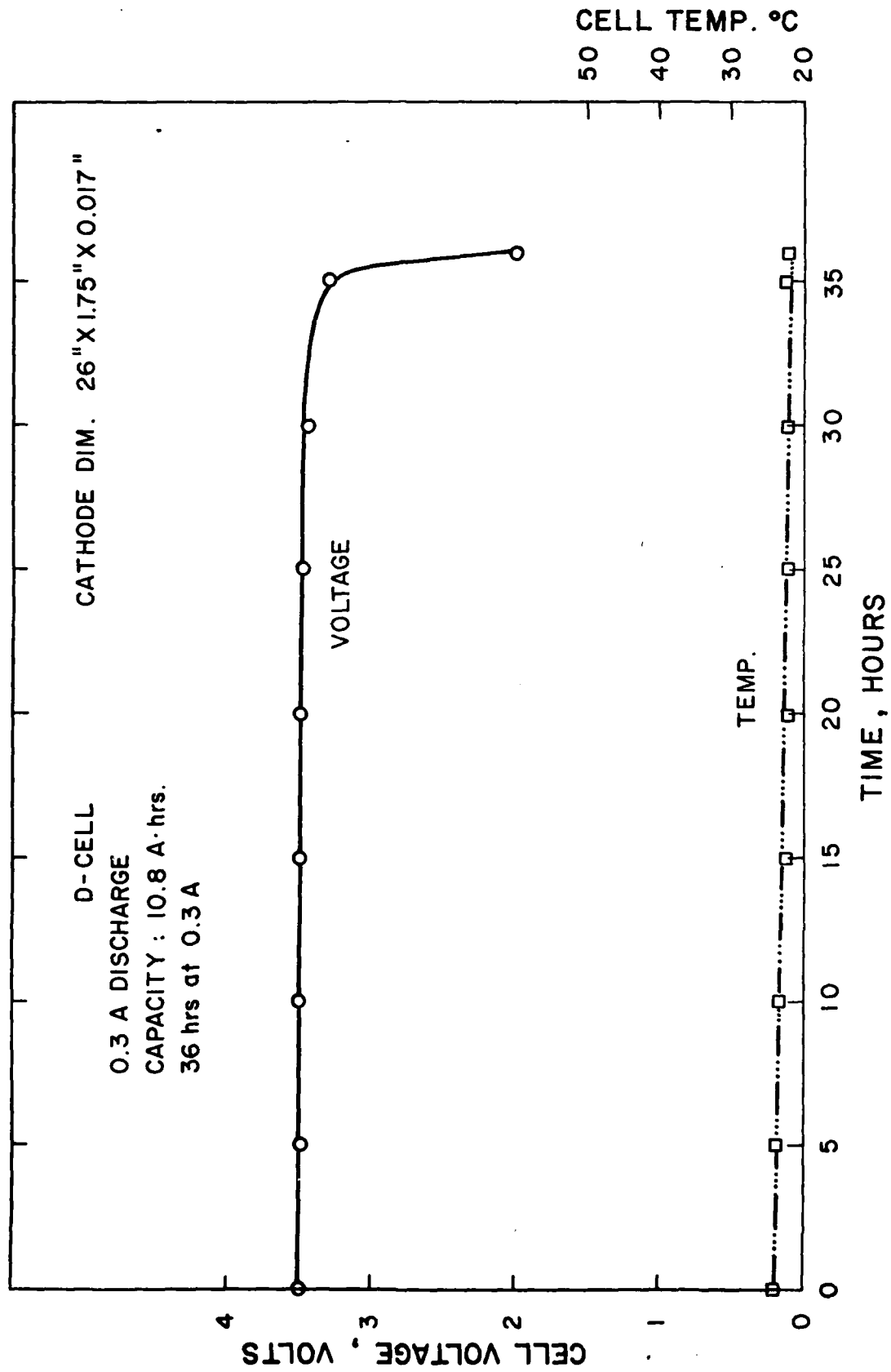


Fig. 12 Performance of a standard high rate D cell on discharge at 0.3A.

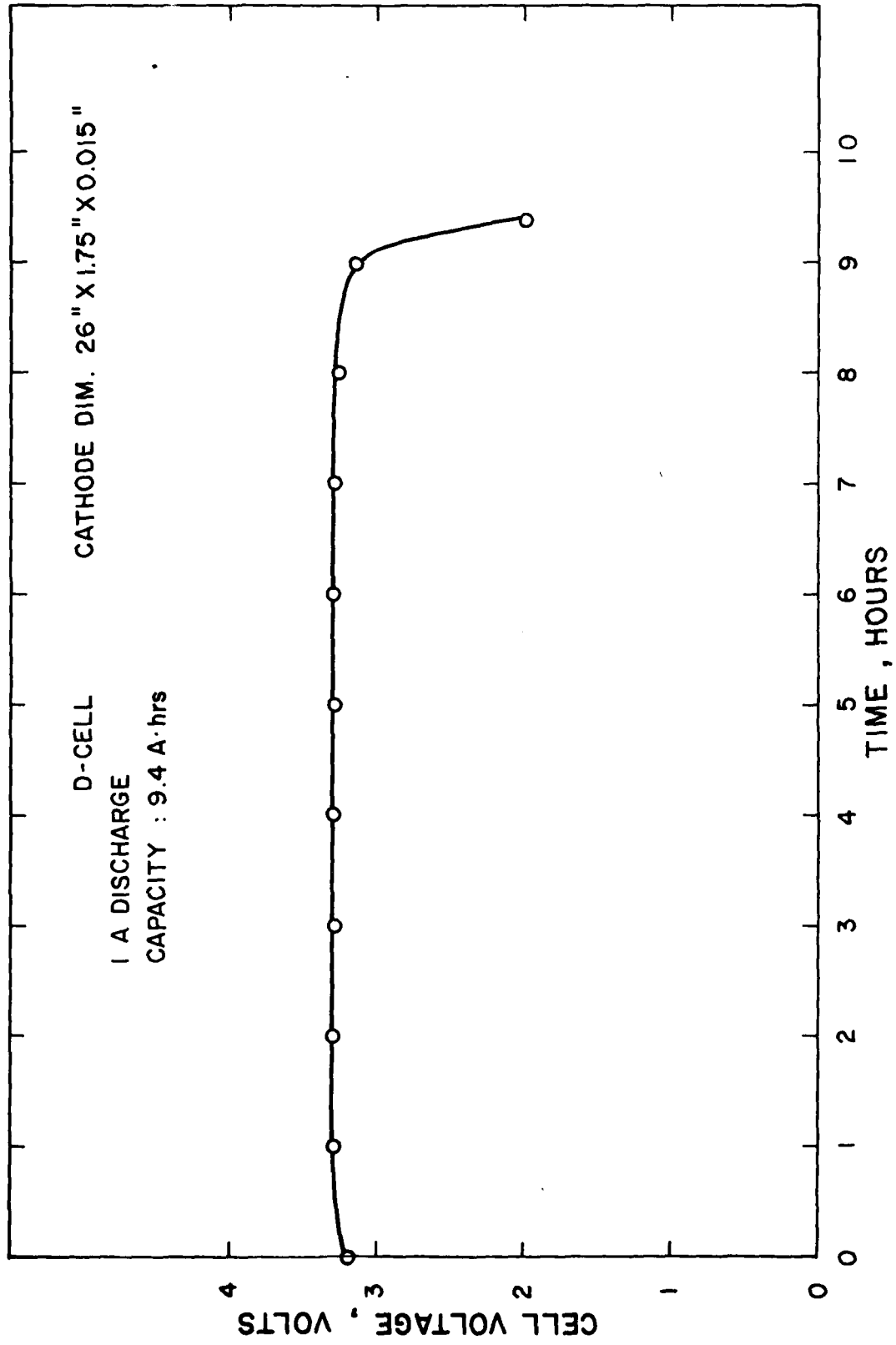


Fig. 13 Performance of a standard high rate D cell on discharge at 1A.



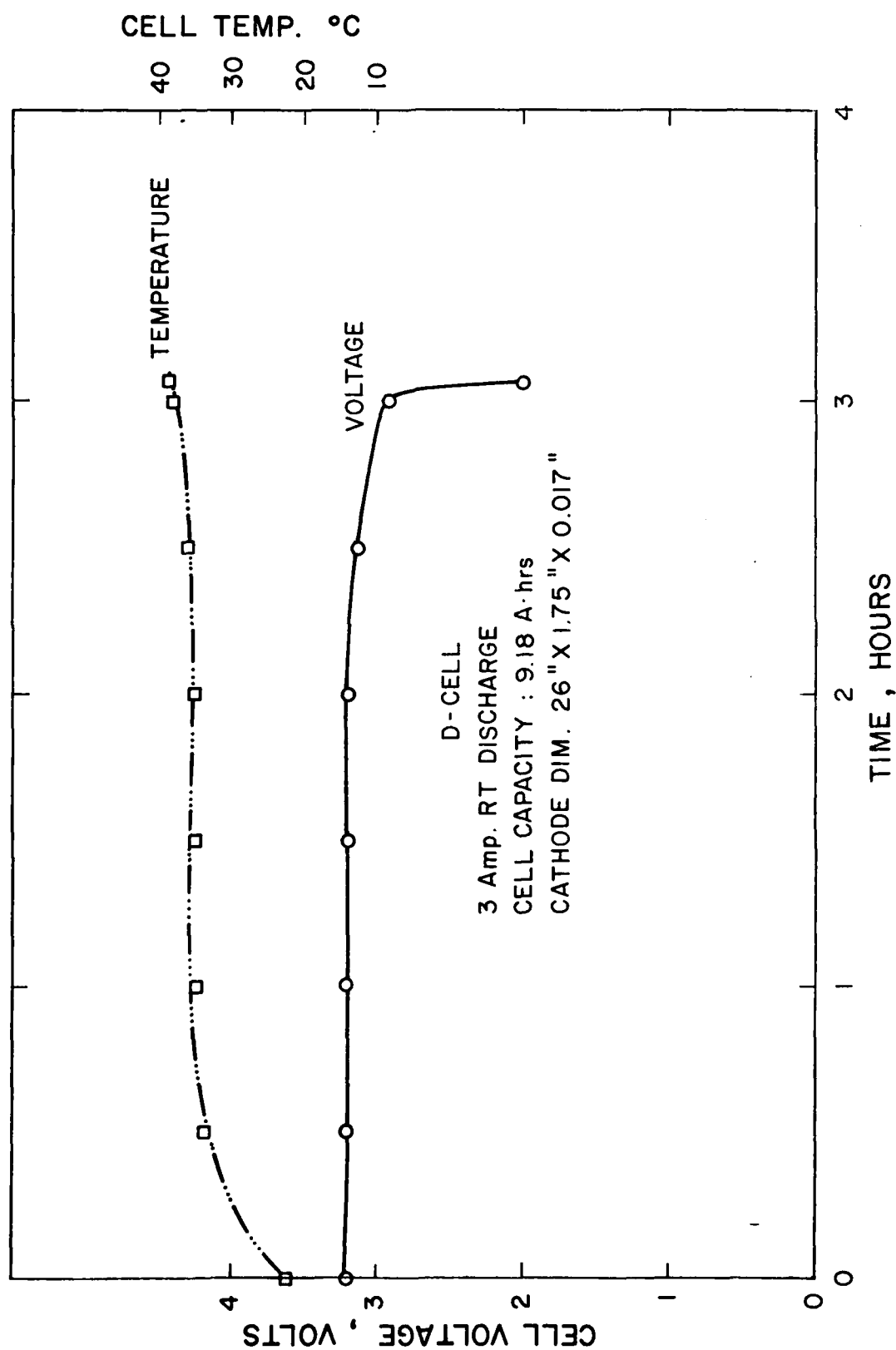


Fig. 14 Performance of a standard high rate D cell on discharge at 3.0A.

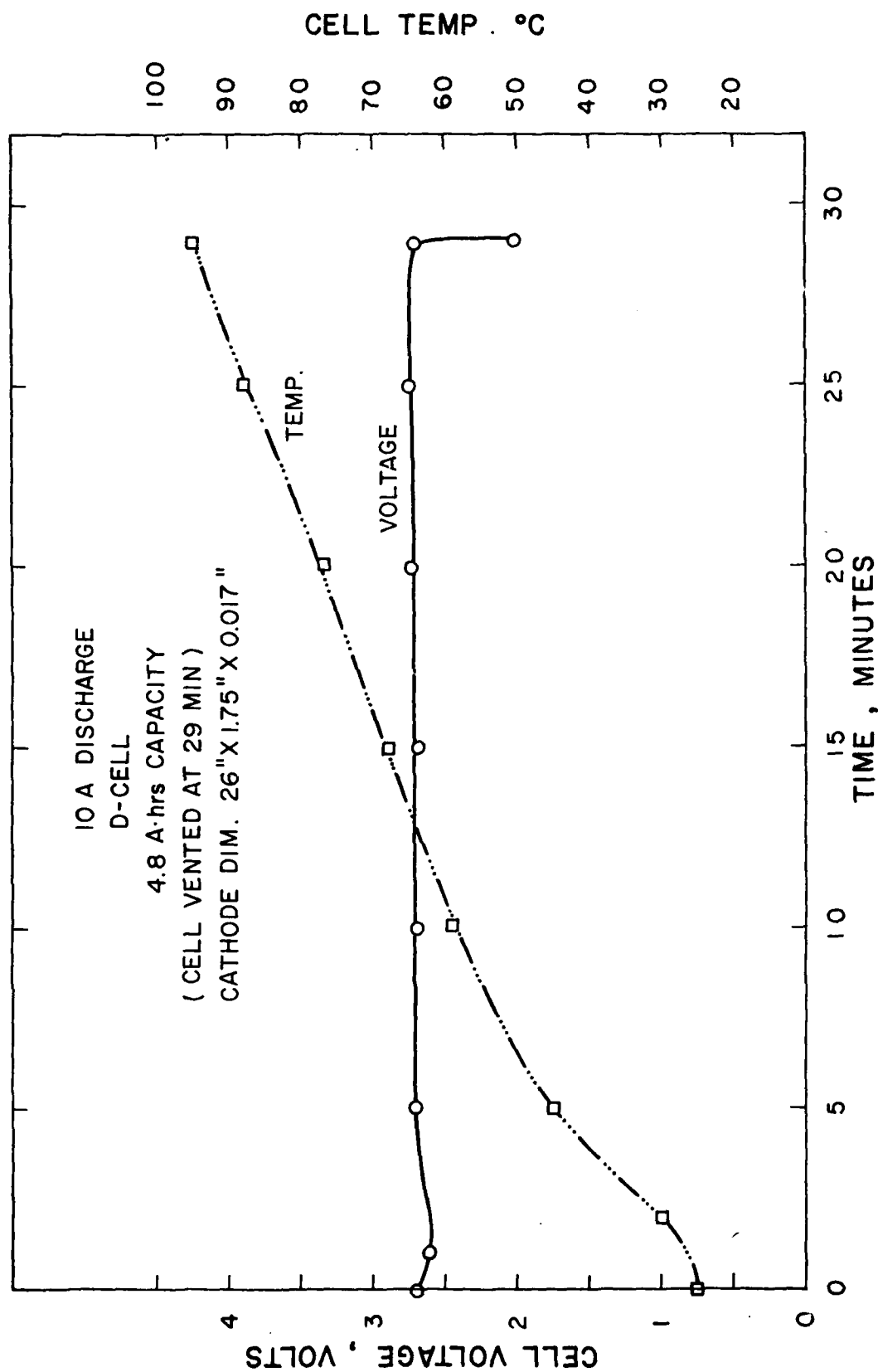


Fig. 15 Plot of cell voltage and temperature for a standard D cell on discharge at 10A.

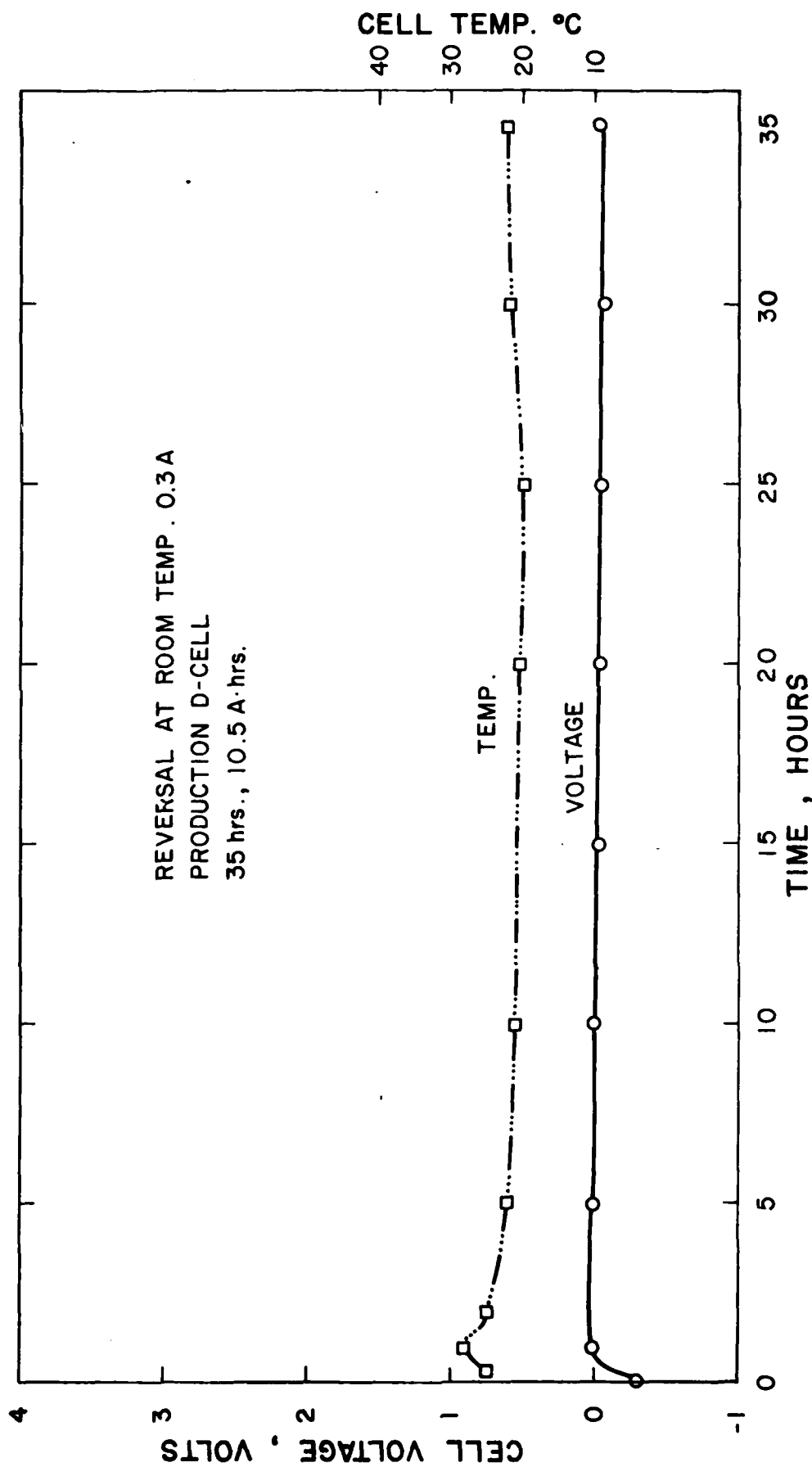


Fig. 16 Plot of cell temperature and voltage for a standard D cell in reversal at 0.3A, room temperature.

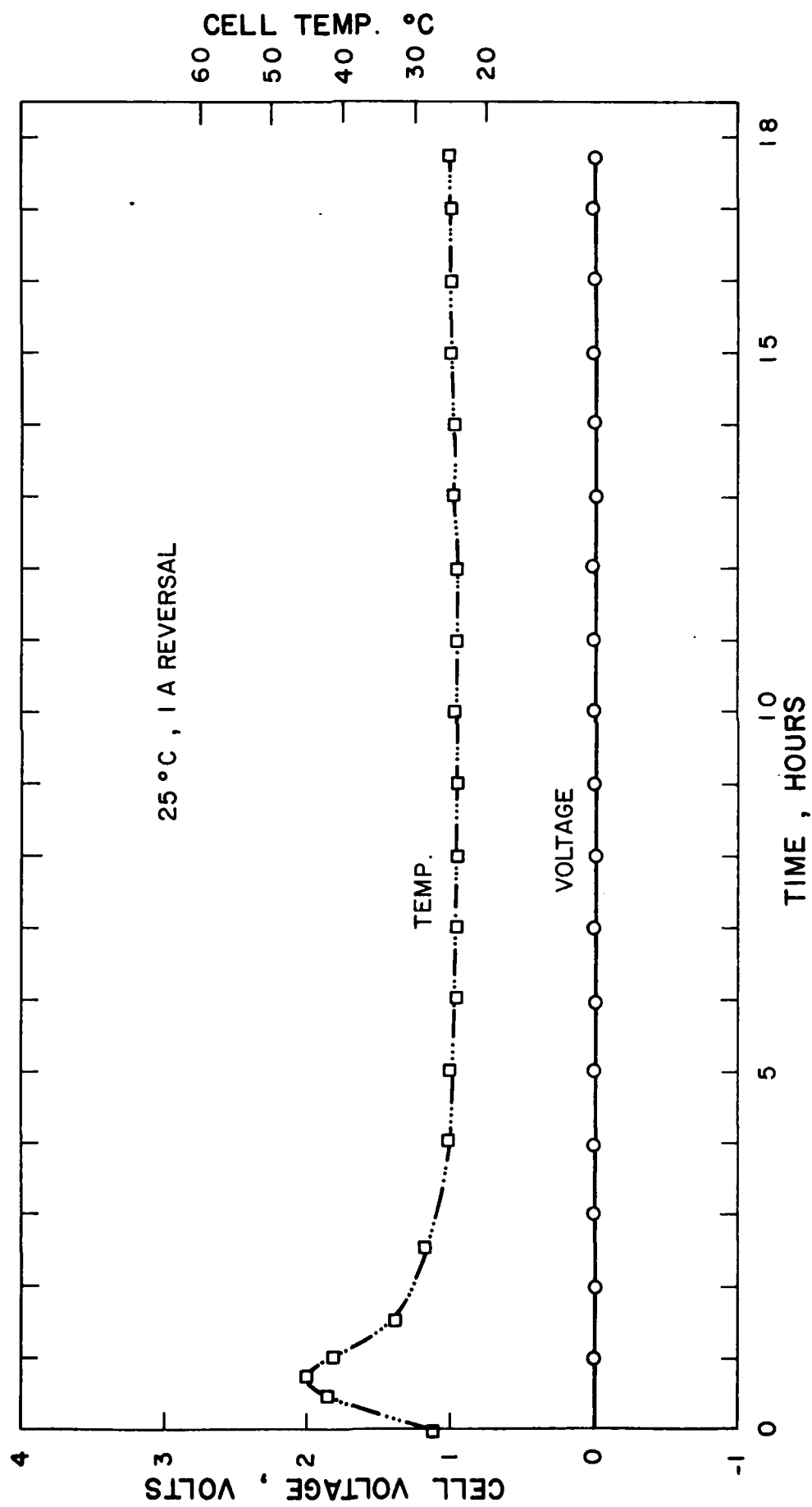


Fig. 17 Plot of temperature and voltage for a standard D cell with cathode additive 2 in reversal at 1A.

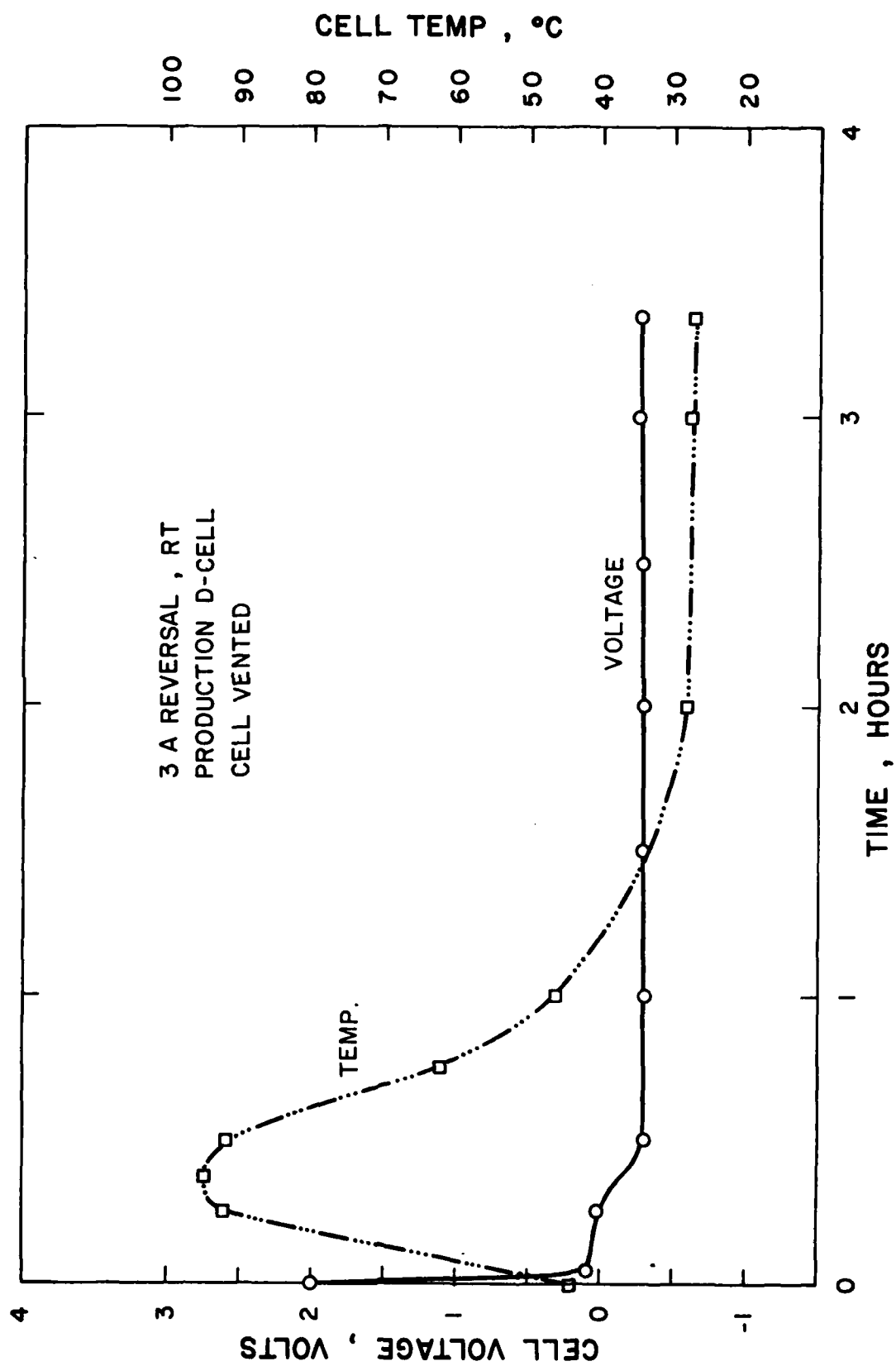


Fig. 18 Plot of cell temperature and voltage for a standard D cell driven into reversal at 3A, room temperature.

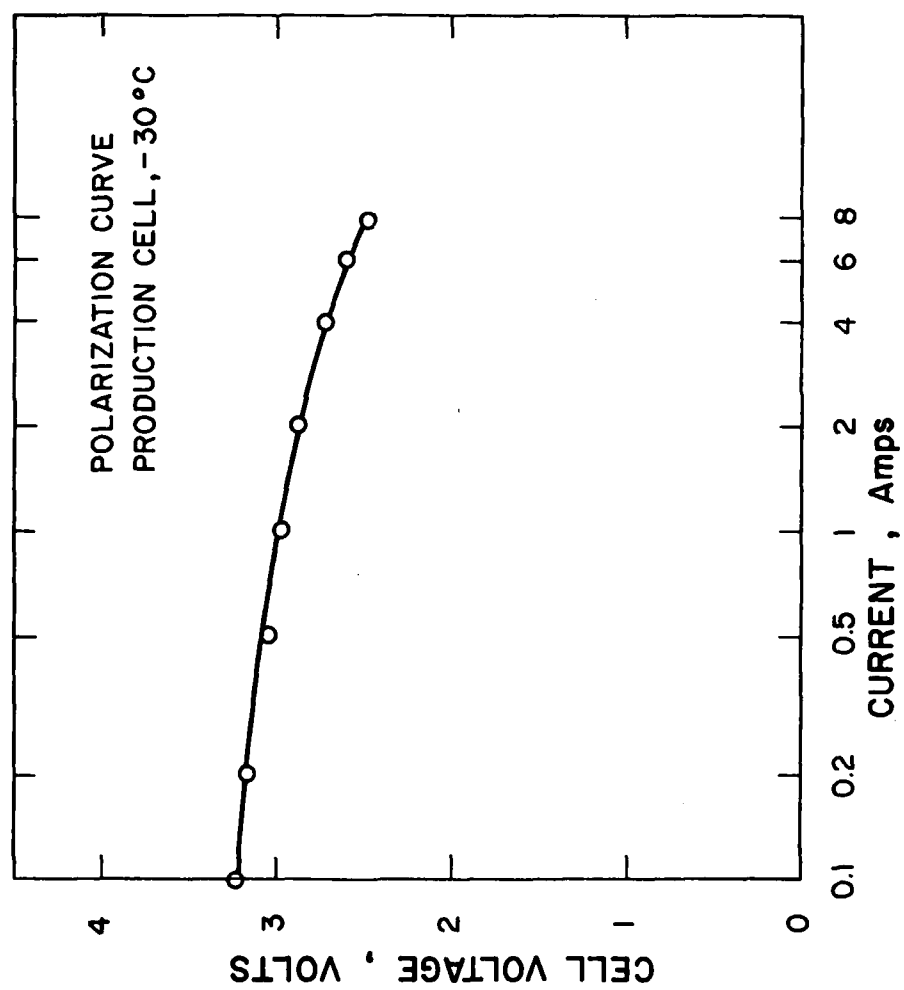


Fig. 19 Polarization of a standard D cell at  $-30^{\circ}\text{C}$ .

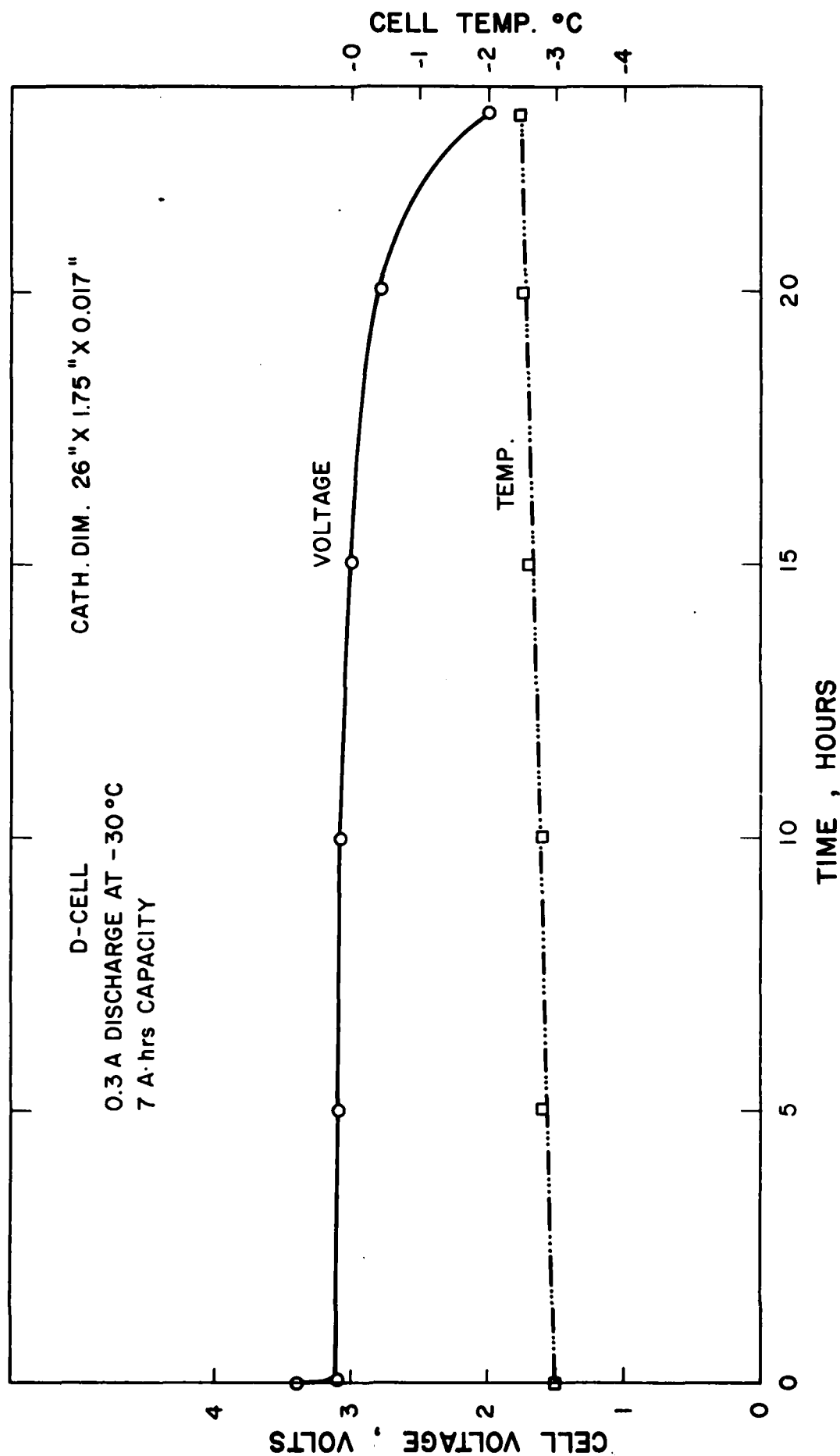


Fig. 20. Discharge of a standard D cell at -30°C and 0.3A

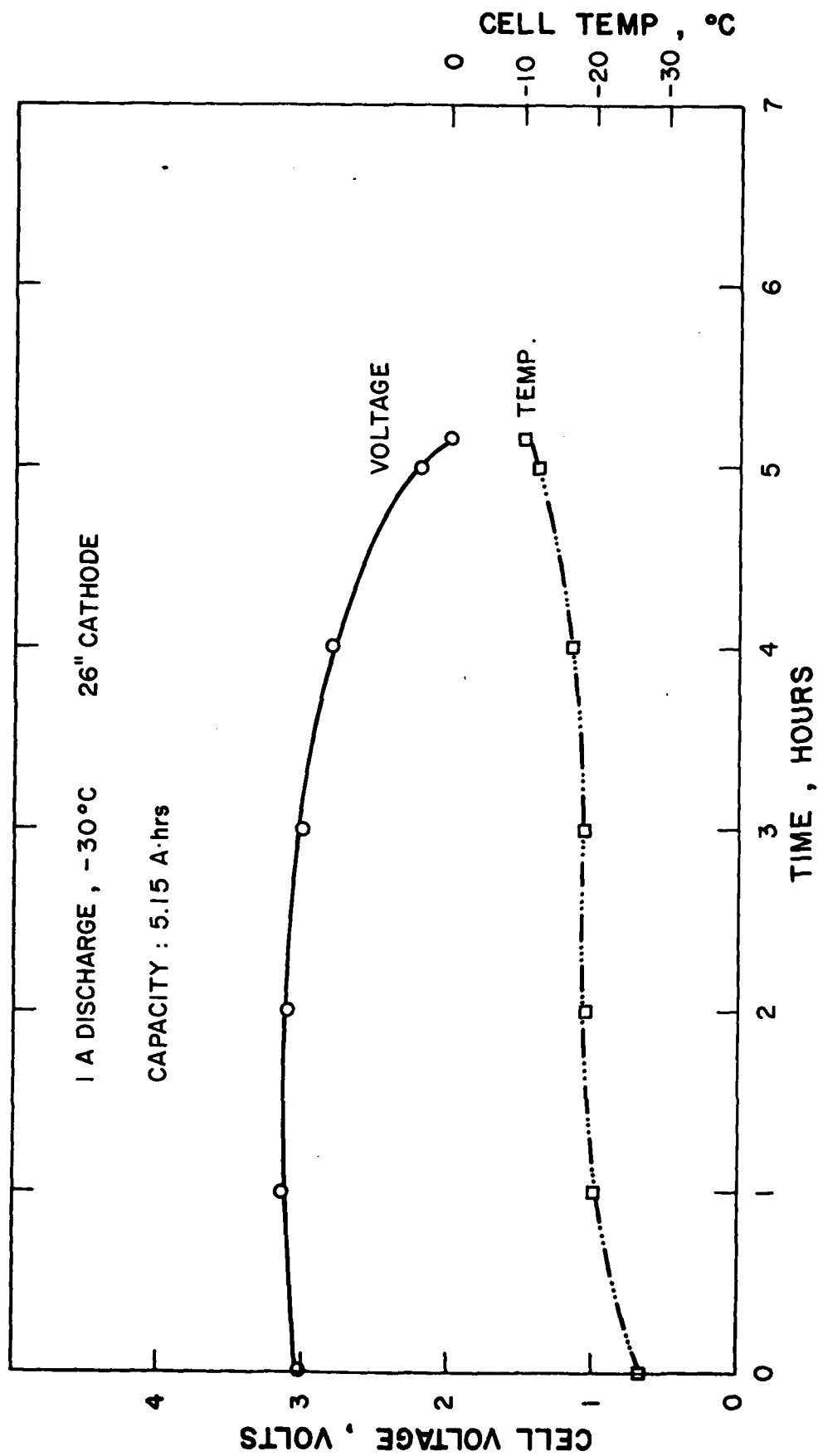


Fig. 21 Discharge of a standard D cell with cathode additive 2 at 1A at -30°C.



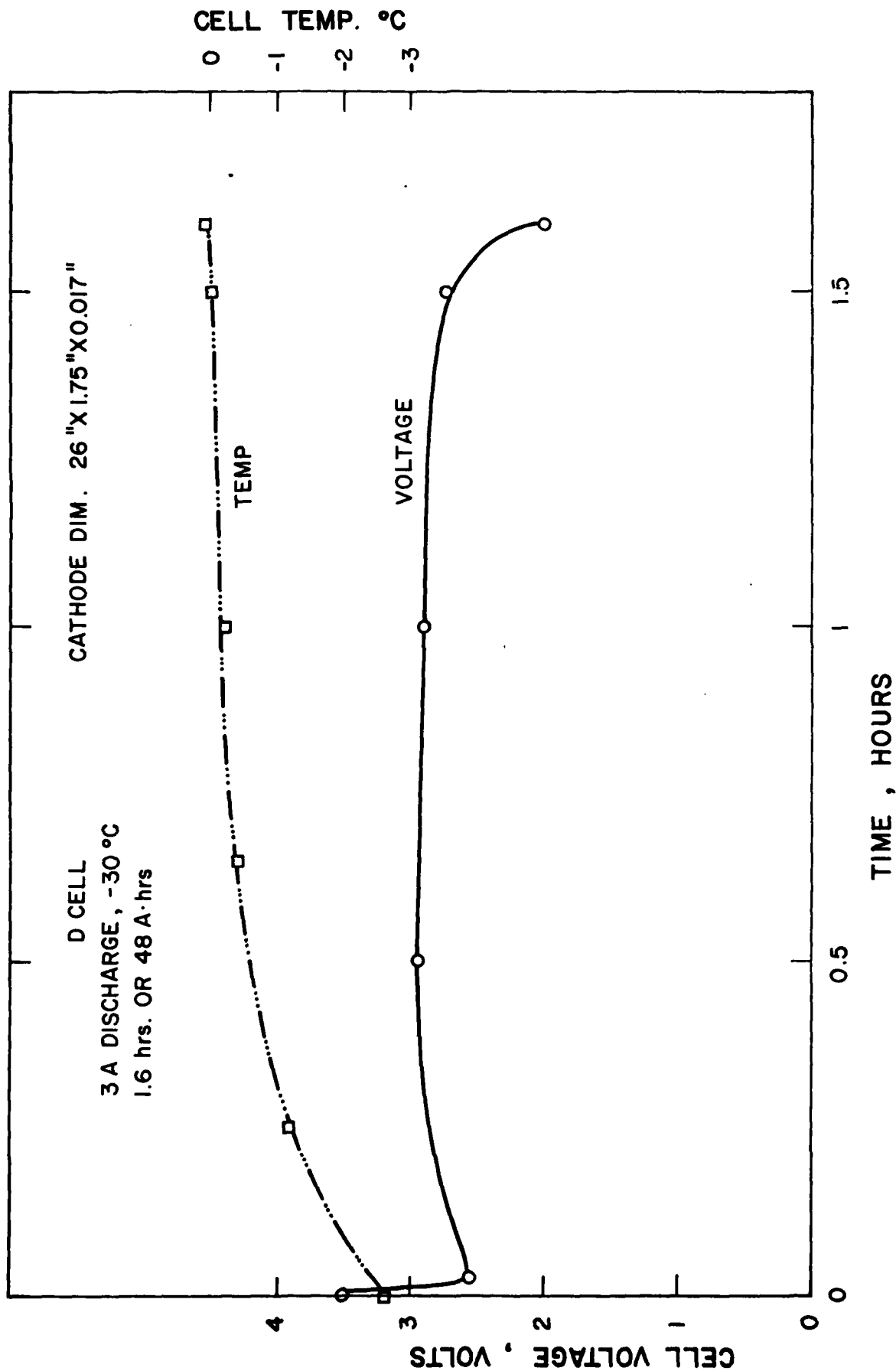


Fig. 22 Discharge of a standard D cell at 3A and -30°C.

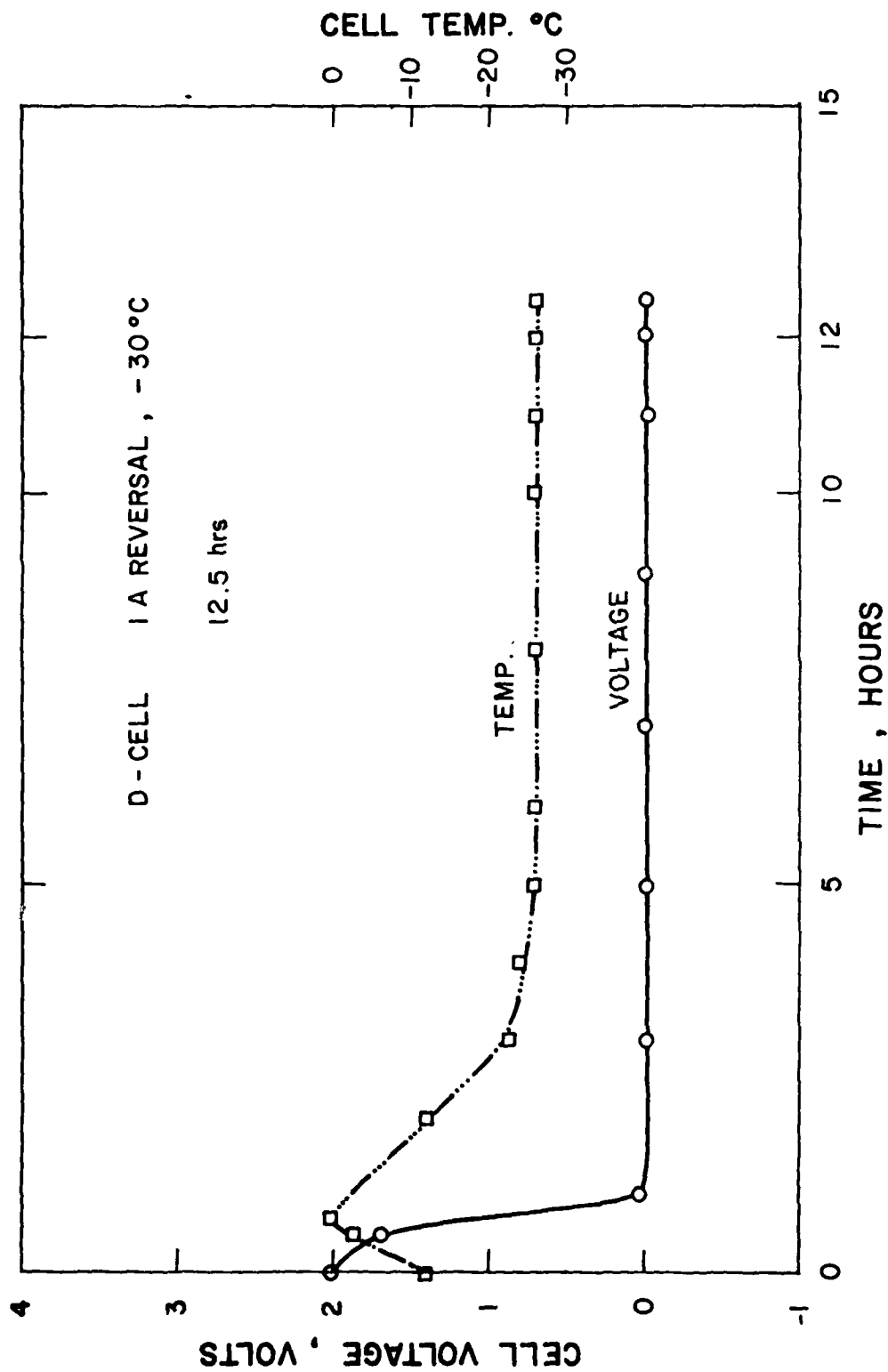


Fig. 23 Plot of cell temperature and voltage for a standard D cell with cathode additive 2 in reversal at 1A at -30°C

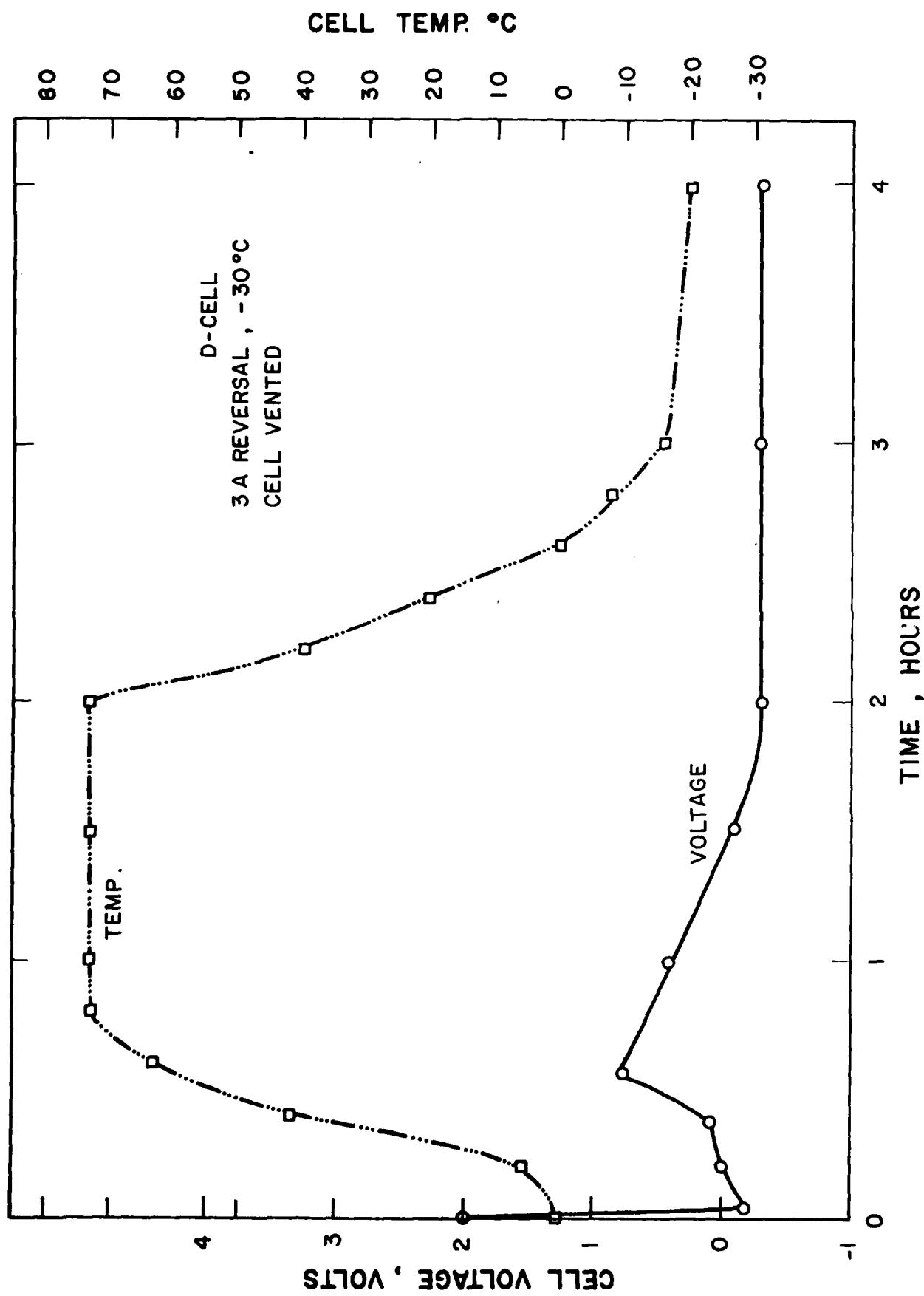


Fig. 24 Plots of cell temperature and voltage for a standard D cell driven into reversal at 3A and -30°C.

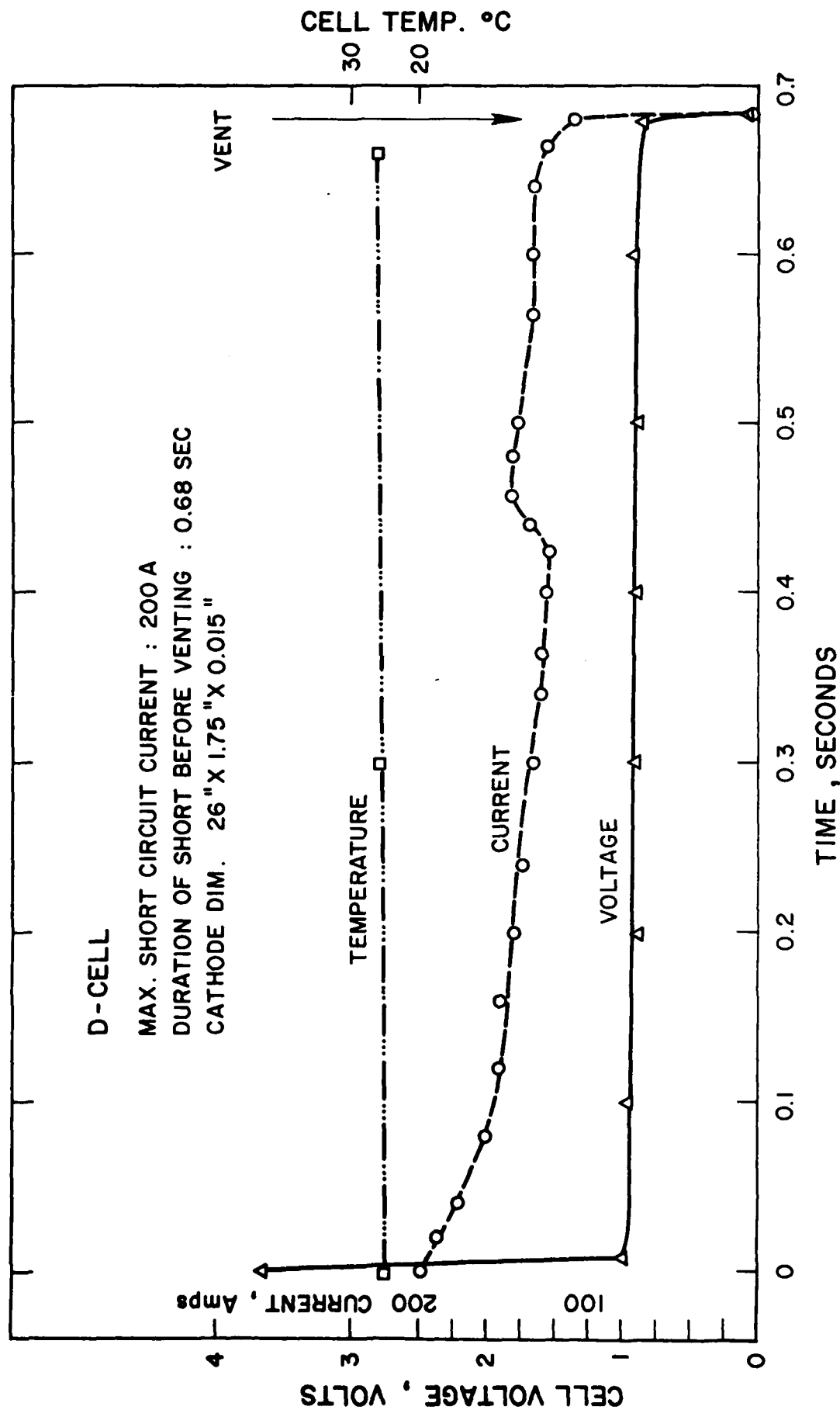


Fig. 25 Plot for a standard D cell with cathode additive 2.

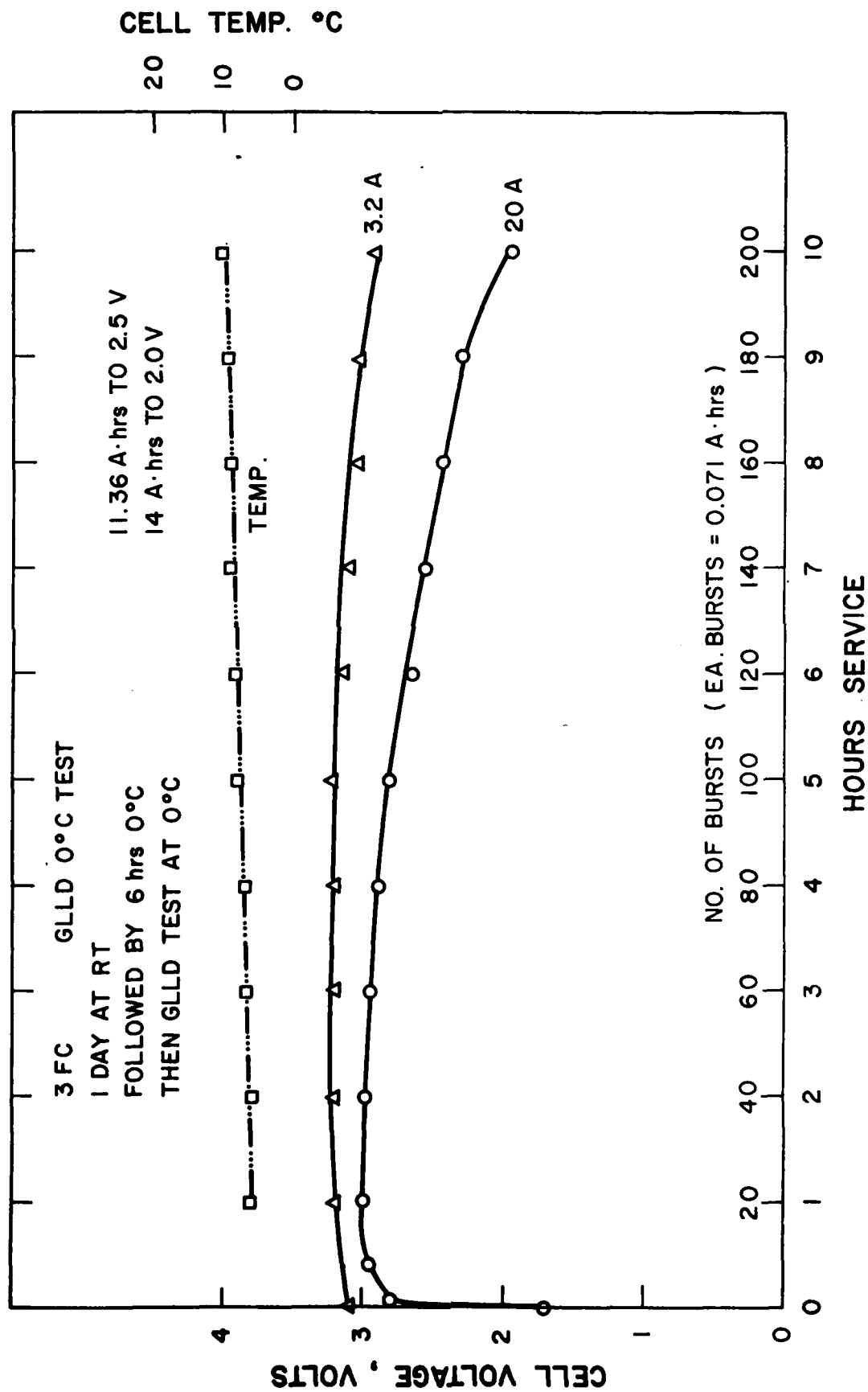


Fig. 26 Performance of a flat cylindrical cell on the GLLD test at 0°C.

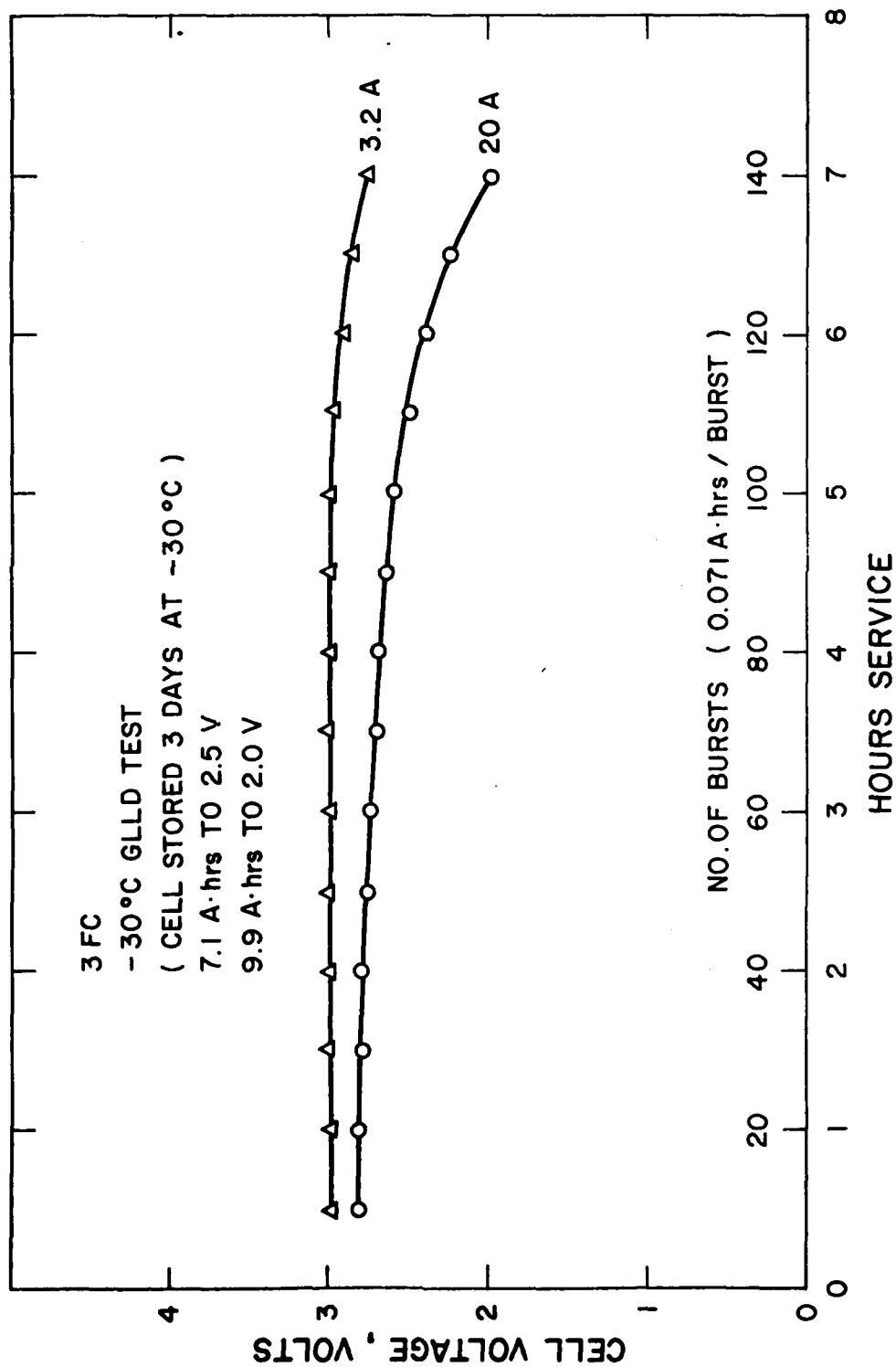


Fig. 27 Performance of flat cell on the GLLD load at -30°C.

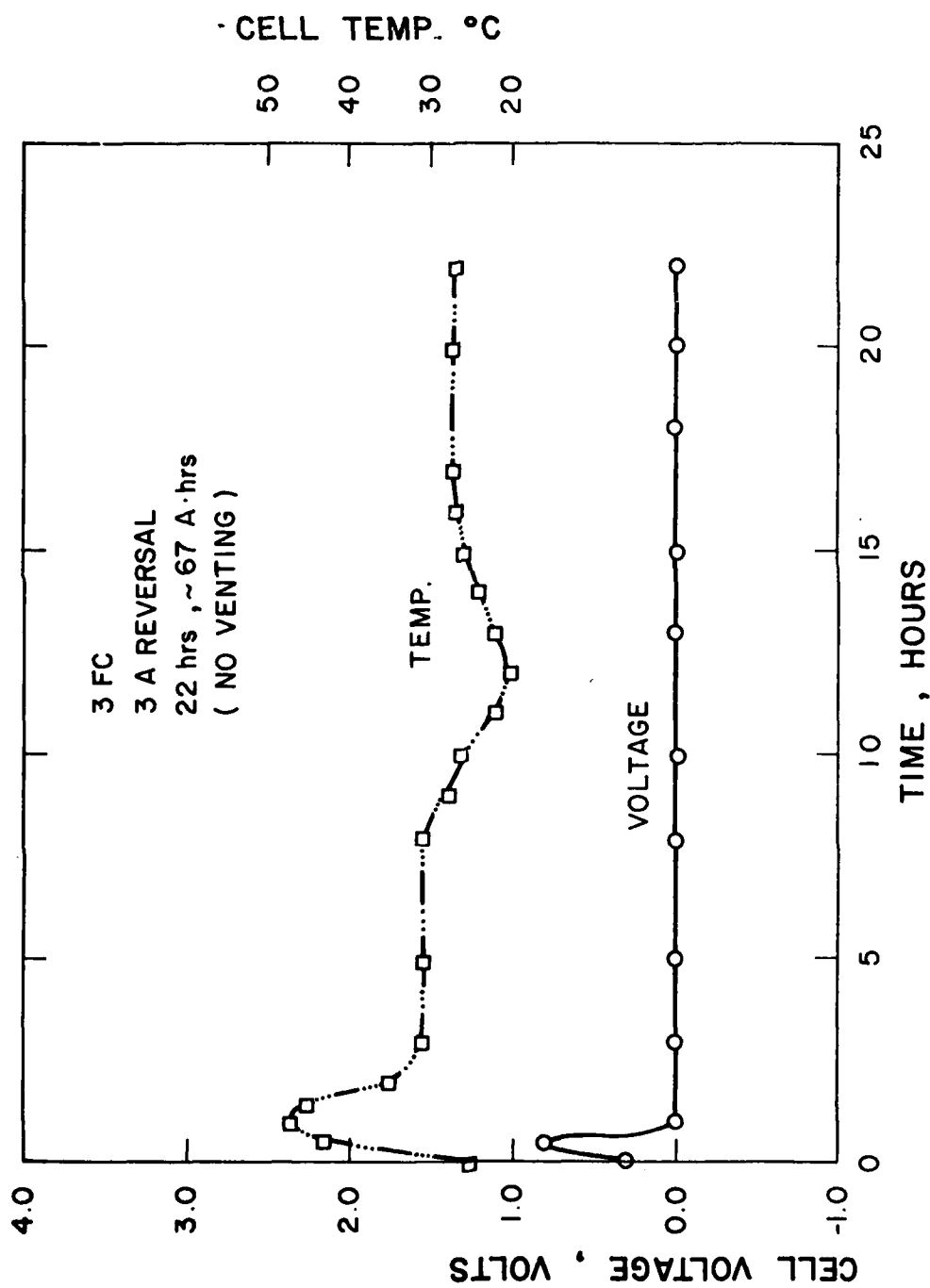


Fig. 28 Voltage and temperature profiles of a flat cell on force-discharge (reversal) at a constant current of 3.0A at 25°C.

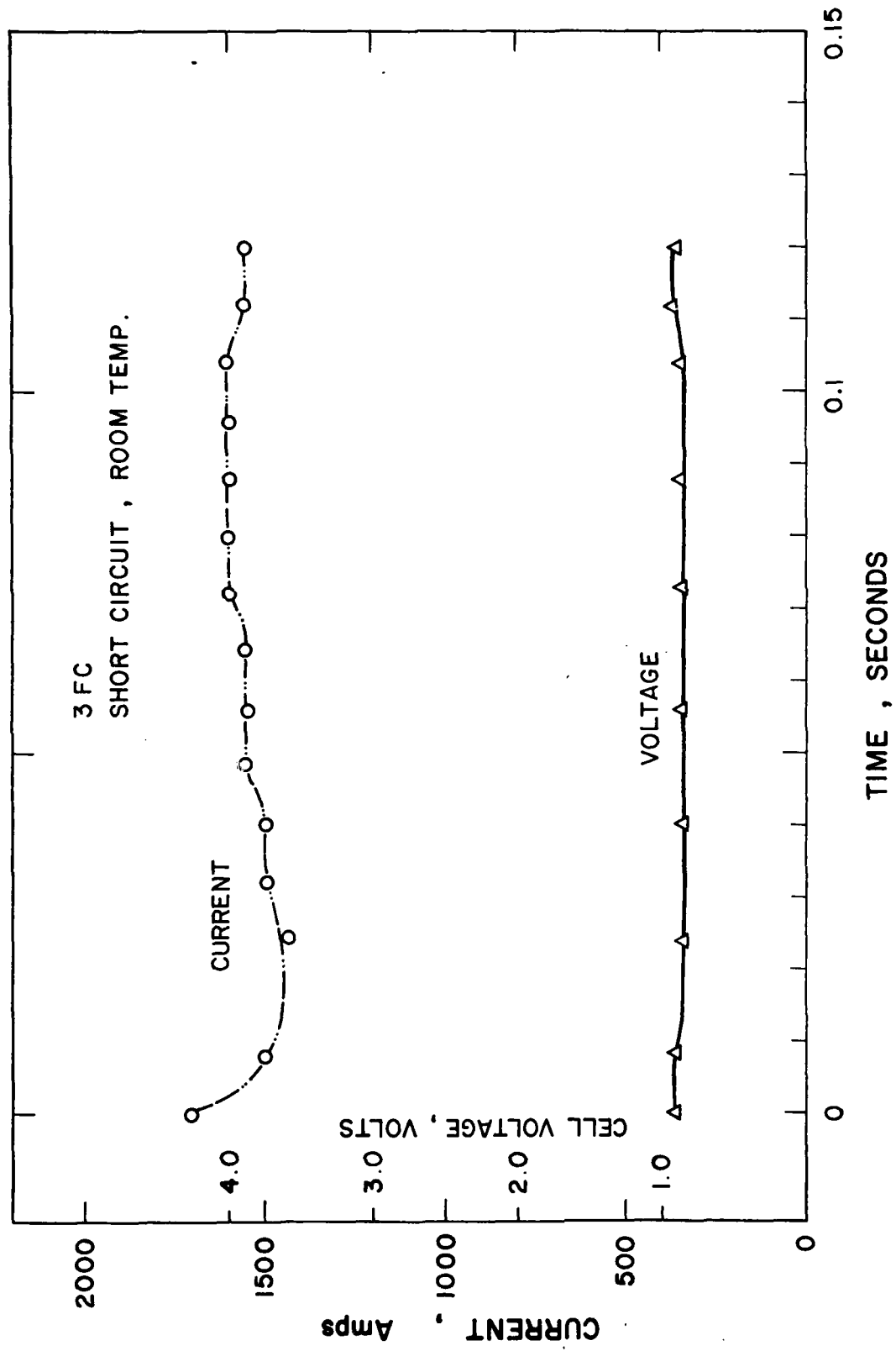


Fig. 29 Short circuit performance of a flat cylindrical cell.



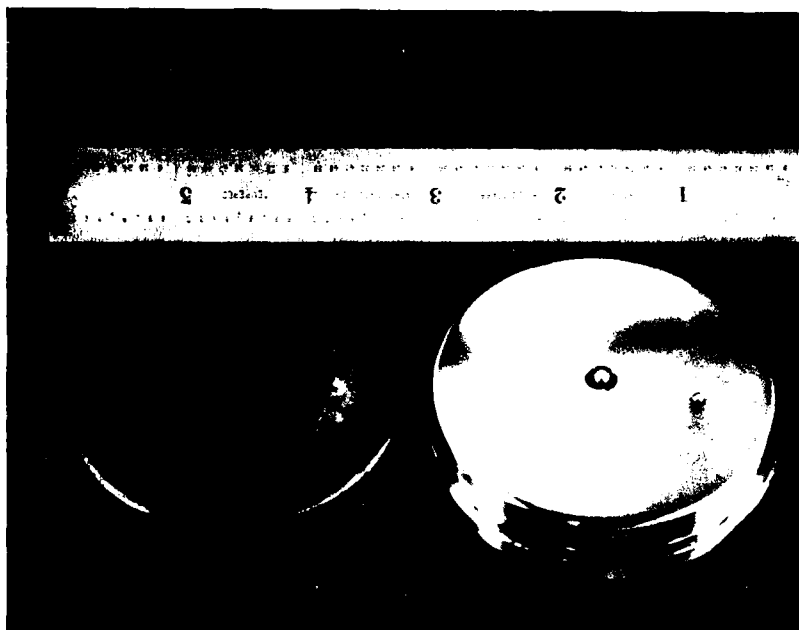


Fig. 30. Photograph of a fresh and a shorted flat cell

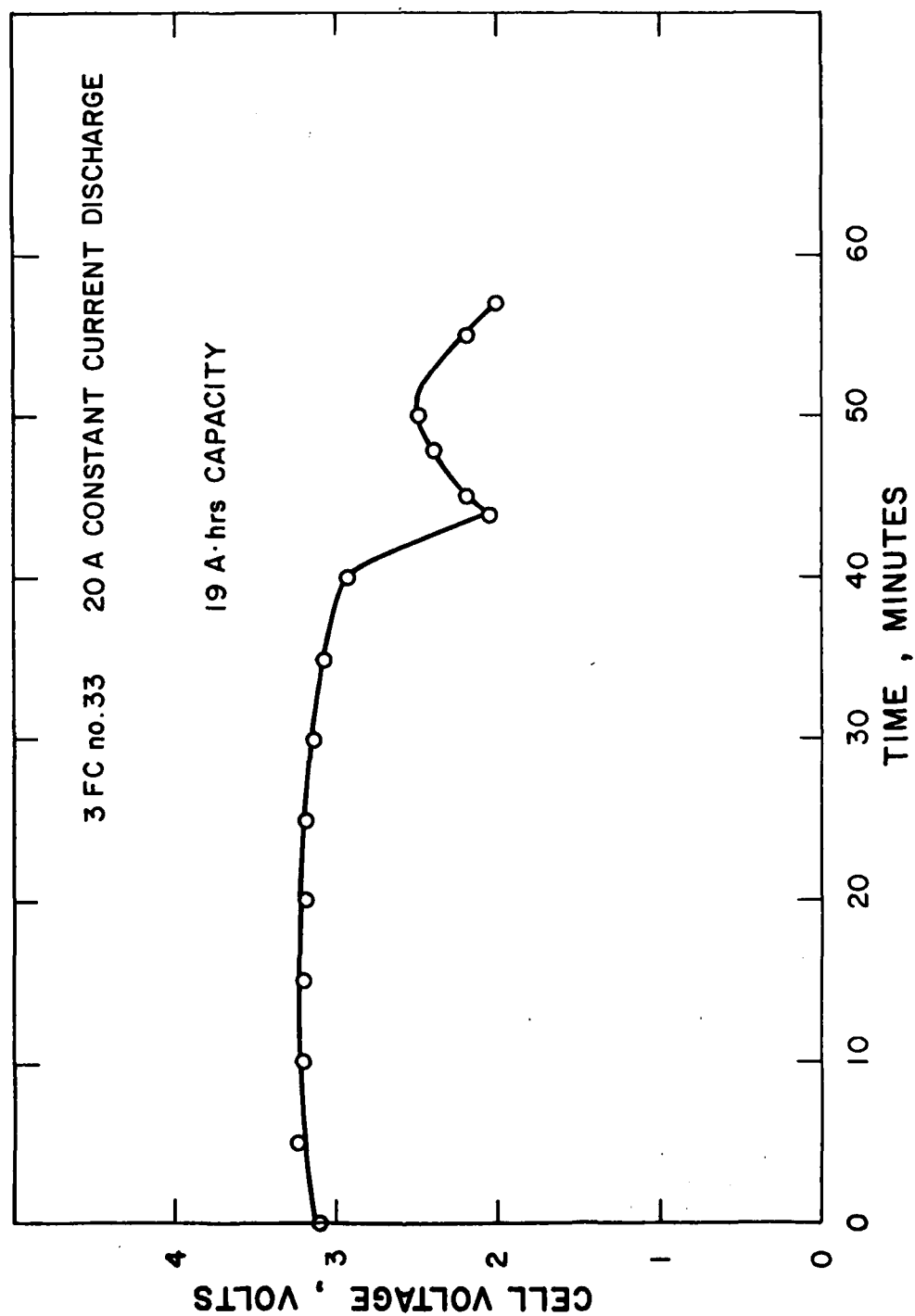


Fig. 31 Performance of a flat cell on 20A constant current discharge.

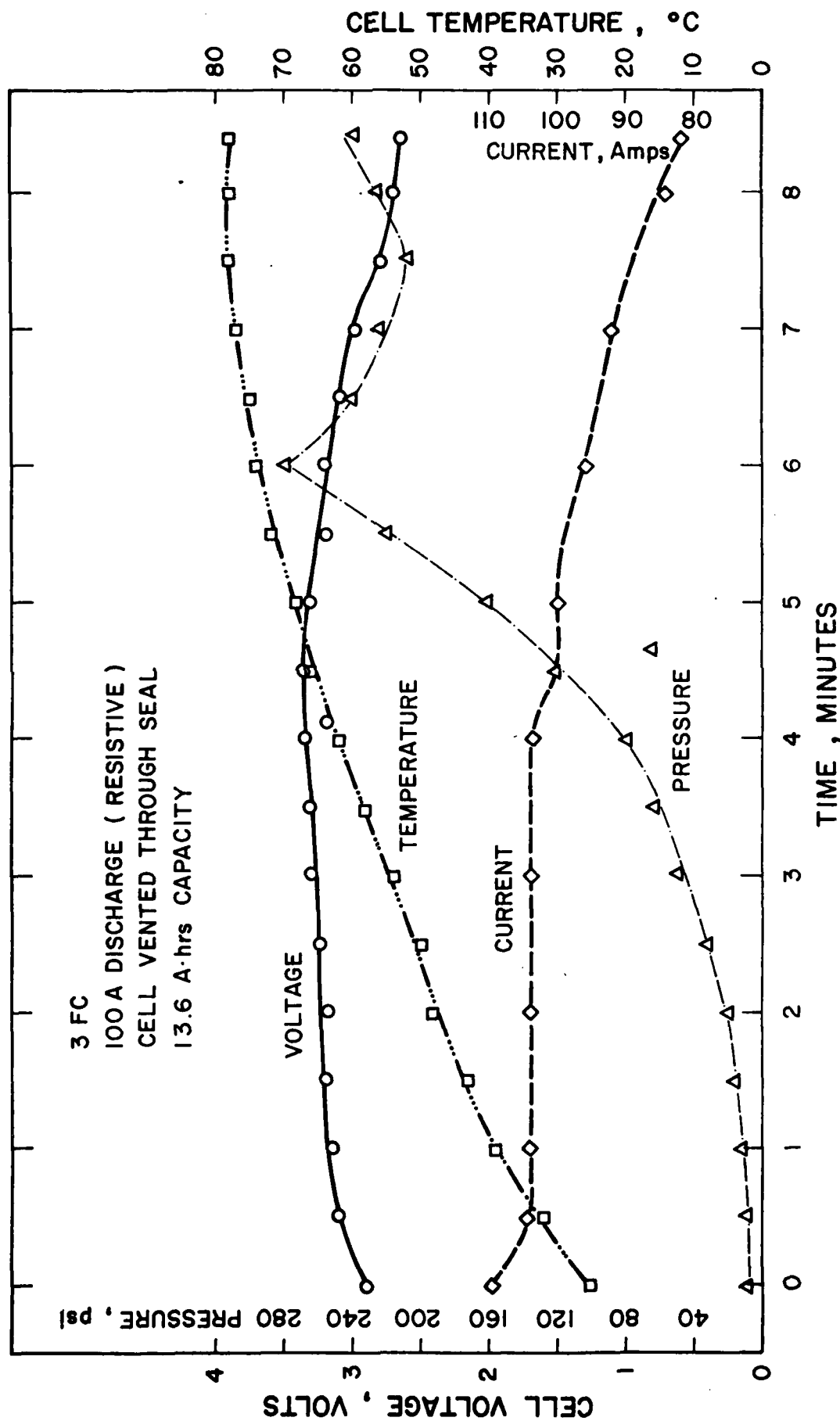


Fig. 32 Voltage, temperature and internal pressure profiles of a cell on 100A discharge at 25°C.

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